(54) Title: FIBER OPTIC BENDING AND POSITIONING SENSOR
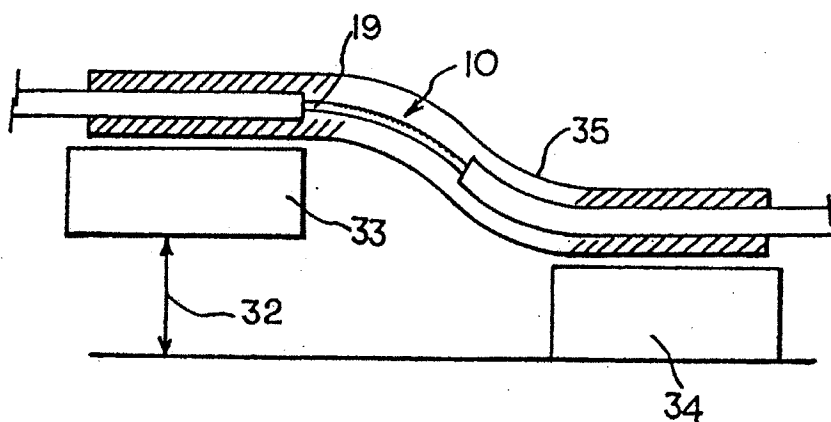
(57) Abstract

A curvature or bending and displacement sensor is composed of a fiber optic or light wave guide (13), for attachment to a member or members being curved or displaced (11). Light is injected at one end and detected at the other end. Curvature of the fibre results in light loss through an emission surface or surfaces (10), sometimes in conjunction with a superimposed curvature in a plane other than that of the curvature to be measured, this loss being detected. The loss of light detection is used to produce indication of curvature or displacement. The light emission surfaces extend in various forms, such as a surface strip or band. Particularly, in an example, the emission surfaces extend in a substantially peripheral direction, or in a substantially curved axial direction when in a curved portion of a curved guide. The placement, shape and configuration of the emission surfaces allow adjustment of the linear range of measurement, the overall throughput of light, and the length over which curvature is measured. Two or more light guides can be oriented to give indication of direction of curvature or displacement.

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FIBER OPTIC BENDING AND POSITIONING SENSOR

BACKGROUND OF THE INVENTION
Field of the Invention

Various methods exist for measuring strain, curvature or displacement of materials or structural members. One well-known method is to measure stress on or in the members using resistive strain gauges arranged on the surface in patterns such that the bending can be inferred from a knowledge of the modulus of elasticity of the member. Under some conditions it is advantageous to measure stress or deformation using optical fibers. Fibers are ideal for many applications because they can be relatively inert to environmental degradation, are light in weight, are not affected by electromagnetic interference, carry no electrical current, and can be very small and flexible, thus having little or no effect on the structure in which they are embedded. It is possible to either cement fibers to surfaces or to embed them inside, such as in fiber/epoxy composites, concretes, or plastics.

Many types of optical fiber sensors have been developed for the measurement of stress and position. Most employ interference techniques to measure changes in length or bend radius of the fiber. Most of these techniques rely on detecting standing waves set up in the fiber by reflecting part of the light back from its distal end. These techniques are very sensitive (comparable to strain gauges) but require complex and expensive measurement techniques such as interferometry or optical time domain reflectometry (OTDR) for their execution. Measurements are very sensitive to changes in temperature, requiring elaborate compensation techniques. Another limitation of many of the interference techniques is insensitivity to direction because the measurement is

2

made by counting the number of interference peaks due
to distortion of a fiber. Thus, for example,
shortening of the fiber is indistinguishable from
elongation, or bending up is the same as bending down;
unless the fibers are arranged in appropriate curves
or other special geometric arrangements.

Equipment for performing interference
measurements tends to be bulky and expensive,
requiring frequent adjustment. It must be capable of
distinguishing peaks at spacings of the order of 0.5
to 1 micron or less. This has limited most fiber
optic stress measurements to tests which can be
performed under carefully controlled laboratory
conditions.

Non-interference techniques can be used to
measure bending in fiber optics. It is well known
that light leaks out of the core of an optical fiber
if it impinges on the cladding at a sufficiently large
angle with respect to the long axis of the fiber. For
every fiber, there is a critical angle dependent on
the indices of refraction of core and cladding, beyond
which light will escape. If the fiber is bent, some
of the light in the core will exceed this angle and
escape. This effect has been used to build
"microbending" sensors, which simply measure the
percentage of transmission of light down a fiber.
These suffer from relative insensitivity (little light
is lost) at small angles. Usually a microbend sensor
consists of a fiber placed in a corrugated fixture
such that a force applied to the fixture will create
many sharp bends in the fiber. Microbend sensors are
used to measure pressures, forces, and displacement.
These sensors also do not measure the direction of the
force unless pre-tension is applied.

Other fiber optic sensors have been constructed
in which the cladding is removed from the core, or the
cladding and some of the core are etched away. These
sensors may be more sensitive to bending than
untreated fibers, but, like other bending sensors
mentioned above, give no information about the
direction of a bend unless they are bent at rest.
They are thus unsuitable for incorporating in a simple
manner in composite structures containing many
parallel fibers with sensory and structural
properties.

Other fiber optic sensors have been constructed
which use thin films in place of the cladding, to give
location information based on the wavelength of the
filter produced by the thin film. This technique
shows no improvement in sensitivity over other fiber
optic sensing techniques, so interference techniques
must be used to obtain useful outputs.

Many sensors are based on measurements of strain,
which is basically an elongation of material.
Although it is possible to use multiple strain gauges
to infer curvature from strain, it is more desirable
in many circumstances to measure curvature directly.
Often, it is desirable to mount a sensor near the
neutral axis of a beam, where there is no strain
associated with curvature of the beam. Often,
curvature is the parameter of direct interest, such as
when measuring deviation from straightness in a pipe
or rod. It is also frequently desirable to measure
displacement between two structures, which can be
inferred from the curvature of a flexible beam or
fiber connecting them. Just as strain gauges can be
used to infer curvature in some circumstances,
curvature sensors can be used to infer strain.

4

Strain gauges have found wide application in a huge variety of measurement tasks; curvature sensors potentially have just as many applications. The following examples cover only some of the potential applications for fiber optic curvature and displacement sensors: measuring flutter and deflection in aircraft wings and aerospace truss structures; measuring deflections on cranes and lifting devices; measuring movement of bridges, dams, and buildings due to earthquakes, settlement, or other degradation; measuring sag and deflections of pipes, rods, cables, and beams; measuring the effects of frost heave on roadways and runways; sensing traffic movements and soil settlement; measuring wind forces on masts and towers; sensing parameters of sports equipment including skis, poles, shoes, fishing equipment, swords, bats, clubs, balls and clothing; measuring deflections on marine equipment including masts, spars, cables, hull plates, struts, and booms; measuring curvatures of vanes, wires, poles and other flexible structures or probes to infer fluid or slurry flow, speed, and direction of movement; measuring vibration and sound levels by means of flexing beams, fibers, or diaphragms; measuring pressures by sensing the curvature of diaphragms or tanks; measuring acceleration in general; measuring deceleration and associated forces for the deployment of airbags; measuring the deflection of support structures to infer applied weight, forces, torques, and deflections; forming multi-degree-of-freedom force and torque sensors; forming input devices for computers including joysticks, keyboards, and levers; measuring joint angles and deflections on robots, automatically guided vehicles, automobiles, trucks, tanks, earth moving equipment, loaders, cranes, ships, airplanes, helicopters, and spacecraft; measuring the deflections

of tire treads and other rubber or elastomeric moving parts; measuring door and wheel positions; measuring pedal, vane, rudder, lift surface, and valve positions; measuring shaft and knob angles, rotations, and positions; measuring liquid levels by deflection of floats or bladders; measuring alignment of automotive, marine, or industrial equipment; measuring positions and motion of reclining seats, chairs, beds, and medical fixtures; instrumenting medical tools; instrumenting prosthetic devices; measuring deflections in the presence of high magnetic fields; measuring magnetic and electric fields by virtue of forces or motion generated in magnetic or electric media attached to a curvature sensor; measuring concentration or presence of liquids, gases, and vapours by virtue of dimensional changes induced in a substrate to which the curvature sensor is attached; measuring temperatures by virtue of dimensional changes induced in a substrate to which the curvature sensor is attached; measuring positions and angles of parts of animal, including human, bodies; and many others.

Generally, fiber optic sensors that must be exposed to harsh environments or that must be embedded, should be intrinsic sensors, that is, sensors that do not rely on light leaving and then reentering the fiber. Thus, sensors that involve light exiting a fiber, reflecting off a surface, and re-entering are not desirable for many purposes because the surfaces may become contaminated, thus changing the light intensity.

A wide variety of intrinsic fiber optic sensors has been described, most of them based on interference techniques. Interference-based sensors, which rely on

6

mechanical changes to the fiber dimensions producing
changes in light interference patterns within the
fiber, are very sensitive to strain but also to
temperature and involve complex and expensive
electronic circuitry. Another drawback is that
usually lasers or laser diodes must be used as light
sources with these sensors, thereby limiting their
durability and longevity, and increasing their cost.

Optical fibers transmit light by virtue of total
internal reflection. The light is contained in a core
of transparent material. Generally, this core is
covered with a cladding layer that has a lower index
of refraction than the core. Because the index of the
cladding is lower than that of the core, rays within
a certain range of angles of incidence with the
core/cladding boundary will be refracted back into the
core upon striking the cladding. If the fiber is bent
in a curve, small amounts of light are lost due to
changes in the angle of incidence at the curved
core/cladding boundary. If the curvature becomes
substantial, significant amounts of light may be lost.
Fibers with a discrete core/cladding boundary are
called step index fibers. Other fibers called graded
index fibers do not have a distinct boundary between
core and cladding, but exhibit a continuous decrease
in index of refraction toward the outer circumference
of the fiber. For simplicity, this description will
use terminology consistent with step index fibers, but
graded index fibers may be similarly treated, as may
other light guides including guides of non-circular
cross section including, for example, a D-shaped
cross-section, rectangular and other polygonal cross-
sections, and of guides with gas or liquid surrounds
instead of conventional solid cladding. It is also
possible to use metal-covered fibers.

"Microbending" sensors are designed to take advantage of this loss mechanism. They generally involve a mechanical structure such as a serrated plate that presses on the fiber, producing a series of substantial local curvatures (bends). The loss of light is used as a signal to indicate displacement of the mechanical structure. Microbending sensors generally do not have a linear loss of light energy in response to changes in curvature, and are otherwise undesirable because of the necessity for a mechanical structure, and the strain which it imposes on the cladding and core of the fiber during deflection. If fibers are used without a mechanical structure to translate displacement into large local curvature, then the light loss due to bending is sufficiently large to be of practical use only when the bending is large. For small bends, such unenhanced microbending sensors are not useful because inadvertent bending of the fiber optic leads carrying light to and from the sensor portion of the fiber will produce changes in light loss that are indistinguishable from those produced by bends of the sensor portion. For these reasons, microbending sensors are generally not used in embedded applications, and rarely are used for measurements of curvature.

It is possible to treat optical fibers so that the amount of light travelling through the core changes more than usual with changes in curvature. Methods generally involve modification of the cladding so that it loses more light than usual over a short length. When straight, more light than usual is lost over the treated zone. When bent, additional amounts of light are lost due to the greater interaction of the treated sides with the light travelling through the fiber. Methods of treatment include abrasion,

8

etching, heat treatment, embossing, and scraping of the cladding. Such treatment can produce a loss of light that is linear with curvature over a wide range, and which is much greater, by orders of magnitude, than the loss produced by microbending or by inadvertent bending of the leads carrying light to and from the sensitized zone.

A drawback of the above method of treatment is that loss is introduced even for a straight fiber, and the modification of the cladding can weaken glass fibers, especially if it involves removal of cladding around the entire circumference of the fiber.

It is undesirable to produce excessive light losses. If loss through the fiber is minimized, it is possible to use an inexpensive light emitting diode as a source of light, and to use inexpensive photodetectors and amplifiers to detect the amount of light being transmitted through the sensor. For this reason, it is desirable to make sensors with as little loss as possible when at the maximally transmissive end of their range (low residual light loss), but with as large a loss as possible due to a change in curvature (high sensitivity). Preferably, the loss should be a linear function of curvature, with the centre of the linear range being at the centre of range of the mechanical quantity (such as curvature or displacement) being measured. These requirements often cannot be met with known sensors, because parameters such as residual light loss and sensitivity cannot be varied independently. For instance, sensitivity to curvature increases as the length of the treated zone is increased, but so does residual light loss.

9

Harvill et al. (U.S. Patent 5,097,252) have described intrinsic fiber optic sensors with the upper surface of the fiber treated to sense bending of fingers and other body parts. Although a monotonic output is claimed, the range of which includes a straight (zero curvature) sensor, the output is not linear and the range is not centred about zero curvature. Danisch (U.S. Patent applications Serial No. 07/738,560 filed on July 31, 1991, and entitled Fiber Optic Bending and Positioning Sensor and Serial No. 07/915,283 filed on July 20, 1992, and having the same title, each naming Lee Danisch as the inventor, and further described in "Bend-enhanced Fiber Optic Sensors," SPIE: The International Society of Optical Engineering, L.A. Danisch, Volume 1795, 204-214, September, 1992, Boston, MA, USA; "Smart Bone," Final Report for Canadian Space Agency Contract 9F006-1-0006/01-OSC, L.A. Danisch, 24 pp., June, 1992; and "Smart Wrist," Final Report for Canadian Space Agency Contract 9F006-2-0010/01-OSC, L.A. Danisch, March, 1993 has described fiber optic sensors with a surface of the fiber treated to emit light at a side with a minimal loss of throughput by means first described in U.S. Patent 4,880,971, also in the name of Lee A. Danisch. The Danisch prior art includes descriptions of linear responses for a wide range of curvatures, a response that drops off as a cosine function for bends in planes not in the plane of maximum sensitivity, and a range centred about zero curvature. Another feature is a light absorbing coating which reduces or eliminates extraneous responses, including non-linearity. Control over the positioning of the centre of the range would open the possibility of mainly using the portion of the range with the highest light throughput (lowest loss), rather than that with the lowest throughput (highest loss) as taught in Harvill.

This would be especially useful if the centre could be adjusted without affecting the residual light loss or sensitivity, or adversely affecting the strength of the fiber. The prior art does not teach how this can be done. The prior art describes sensors for which it is possible to vary the length, width and shape of a single treated strip, or the depth of multiple notches. Danisch, (U.S. Patent filings above) describes long sensors "...formed by alternating lengths of fibers with an emission strip with lengths of fully clad fibers." However, it is not shown how this technique can be used to gain control over the placement of the centre of the linear range.

A complicating factor in the manufacture of treated fiber optic sensors is that if their response to curvature is maximum in a given plane due to treatment not including the entire circumference of the fiber, then it can be difficult to maintain a proper orientation of the plane of maximum sensitivity after treatment but before embedment of the fiber. The main problem is the ease with which the fiber can twist about its long axis due to torques applied at any point along the length of the fiber. This is a problem for any fiber whose complete circumference is not treated, including fibers that are treated at both the top and bottom, thus having a response characteristic that does not distinguish upward from downward bends, but that distinguishes (through a cosine law) between up/down and left/right bends.

Another complicating factor in the design of many intensity-based fiber optic sensor system is the need for a return path and a means of reflecting or turning the light at the end of the fiber run.

To eliminate the need for a turnaround and return path, a coupler is often used at the measurement end, such that light can be injected into a single fiber with a reflector at the end. Injected light travels through the treated portion of the fiber, is reflected at the end, and returns to the coupler in the measurement system in the same fiber. The coupler is designed to extract the return light only, passing it on to a photodetector and amplifier. Unfortunately, the coupler introduces large losses and can be expensive to manufacture. Also, the reflective structure at the end can be lossy and difficult to manufacture.

In other cases, it is acceptable to use a return fiber with a reflective structure placed near the ends of the sensor and return fibers, whose distal ends face or are inserted into the reflective structure. Such a solution generally involves light leaving and re-entering the fibers, so that the sensor is no longer an intrinsic one, or it involves losses that may be unacceptable. It also invariably involves a reflective structure that is larger than the diameter of a single fiber or even two fibers, and is thus unacceptable for embedment.

A disadvantage of a turnaround loop at the distal end of a fiber optic sensing system is that even if sufficient width is available for the turnaround, it requires adding extra length to the system beyond the location of the sensor. This increases the size of the system and prevents sensing at the distal end of the system. For instance, it may be desirable to measure changes in curvature at the top end of a non-hinged but flexible lever which is being used as a "joystick" form of input device for a computer. If a

12

turnaround loop is used for a fiber that enters the
lever at the bottom, it would normally be at the top
of the lever, thus not allowing known forms of
curvature sensors to be placed at the top. As another
example, if a turnaround loop is used and it is
desired to measure curvature at the centre of a curved
beam, then the beam must be long enough to accommodate
the turnaround.

Another disadvantage of the turnaround is that it
must be held in position to avoid changes in light
intensity due to changes in curvature within the plane
of the turnaround, particularly if the turnaround has
a small radius of curvature which is producing light
losses substantially greater than those of a straight
fiber. If the turnaround is rigidly affixed to the
substrate, this may produce stresses on the fibers
between the turnaround and the location of the
sensitized zone, which must also be rigidly attached
to the substrate in order to properly sense its
curvature.

However, if the disadvantages of the turnaround
can be overcome, it has overwhelming advantages in
terms of cost of manufacture, small size, lack of
complexity, and relatively low light loss.

The present invention provides an improved sensor
means for sensing curvature and displacement with
minimum manufacturing cost and minimum damage to the
fiber.

An object of the present invention is to provide
a sensor means which minimizes residual light loss
while optimizing sensitivity and preserving the
strength of the fiber.

A further object of the invention is to provide
a sensor means which allows maximum utilization of the
portion of the linear range exhibiting the greatest
transmission of light through the fiber.

A further object of the invention is to provide
a sensor means that allows achieving a given residual
light loss and sensitivity over a range of sensitized
zone lengths.

A further object of the invention is to provide
a sensor means which allows placing the sensitized
zone of the sensor near the distal end of the sensor
system.

A further object of the invention is to provide
a sensor means which maintains the orientation of the
sensitized zone, once treated.

SUMMARY OF THE INVENTION

This invention achieves these and other results
by providing a treatment means that minimizes residual
loss and maximizes the effect of mechanical curvature
of the sensor on the transmission of light through the
fiber.

In one embodiment of the present invention, the
sensor zone is made up of alternately treated and
untreated portions of the fiber. There is opportunity
for many light rays to refract toward the core from
untreated spaces between treated ones so that average
curvature may be sensed over a long length of the
fiber without introducing unnecessary residual loss.
The treated portion or portions may involve
modification of the fiber for its entire periphery or
a part of the periphery. Treatment may include

14

abrasion, etching, repeated notching within the band,
heating, chemical removal, and others. Treatment is
generally accompanied by application of at least a
thin layer of light absorbing material.

In another embodiment of the present invention,
treatment of portions of the fiber mentioned above
involves modification of only a portion of the
periphery, these portions being oriented on the side
of the fiber that is concave outward over a desired
range of curvatures. By varying the lengths of
treated and untreated strips, and the number of
strips, and the extent of the periphery treated by
each strip, the size of the linear region of
sensitivity for concave bends can be increased, so
that the sensor is operated near its maximum
throughput condition. This embodiment has the
advantage of allowing operation of the sensor within
its highest linear throughput range, and controlling
the size and placement of the centre of that range,
while maintaining linearity of response to bending and
displacement. The method has the advantage of being
able to produce a sensor that has a minimum amount of
periphery treated, while still providing maximum
sensitivity and throughput over a desired range. This
is important to maintaining the strength of the fiber
used, especially when glass fibers are being treated.

In another embodiment of the present invention,
the turnaround at the distal end of the fiber sensor
loop is treated to be sensitive to bending, such that
the treated portion has a minimal effect on throughput
of the turnaround, but the sensitivity to bending is
the same or improved over that of a sensitized zone
placed on a straight portion of the fiber. In this
case, the net throughput of the sensitized zone and

15

the loop combined can be made greater than for a
sensor fiber in which the zone and loop are separated.
The sensitized turnaround loop makes it possible to
sense curvature at the free end of a structure, and
has the added feature that if the turnaround loop is
heat-formed or constrained by a form or fixture, it
forms a plane that is always orthogonal to the plane
of maximum sensitivity of the sensor, so that it is
easy to maintain orientation of the maximum
sensitivity plane during manufacture. The structure
also lends itself to easier manufacture, because the
turnaround forms the distal end of the fiber loop, and
can easily be inserted into a machine for heat
treatment, embossing, sanding, or other operations.
This is not the case for a fiber which must be treated
at some arbitrary location along its axis, especially
if it must be inserted into an oven for heat
treatment, without involving the leads in the
treatment. This embodiment can be used with various
forms of treatment, including treatment of various
portions or all of the circumference.

The invention may be defined as a fiber optic
curvature and displacement sensor comprising a fiber
optic light guide having at least one light emission
surface extending, for part of the length of the
guide, in a direction selected from: a substantially
circumferential direction, and a substantially curved
axial direction when in a curved portion of a curved
guide.

In one preferred embodiment, the light emission
surface is in the form of a plurality of
circumferentially-oriented bands.

16

In another preferred embodiment, the light emission surface is in the form of at least one ring around the circumference.

In a further preferred embodiment, in a fiber having a rectangular cross-section, the light emission surface is on one of the sides of the rectangle, or on opposed sides of the rectangle. Preferably the rectangle is oblong, with the light emission surface or surfaces on one or both longer sides, respectively.

Preferably the light emission surfaces are positioned to give the most desirable orientation to the maximum sensitivity plane.

The fiber optic light guide may be in the form of a loop, the loop having at least a substantial portion of the light emission surface or surfaces therein. These latter surfaces preferably are in a configuration selected from peripherally-oriented bands grouped on an inside or concave portion of the curvature of the loop, and axially-oriented bands substantially parallel to the plane of the loop and substantially following the curvature of the loop.

In one preferred embodiment, from three to five circumferentially-oriented bands are grouped together with the bands each extending for about 60° to about 90° of circumference. In the case of axially-oriented bands, preferably from two to six curved bands are either coplanar or in parallel planes. The invention includes sensors in which the fiber optic light guide, or portion thereof, is in the form of a single fiber which, serves both to illuminate the light emission surface or surfaces, and to collect illumination which has passed the light emission surface or surfaces, the

17

illumination end and collection end of the fiber being located in a single region removed from the light emission surface or surfaces.

In a further preferred embodiment, the fiber is in the form of a flat strip, having a generally rectangular cross-section having spaced parallel opposed wide sides. The light emission surface or surfaces are formed on one or both of the wide sides. In particular, the light emission surface or surfaces are formed at a bend in the fiber, or may include both axes. The bend may be in the plane of the wide axis of the fiber, or in the plane normal to the wide axis of the fiber. One example of a strip-type fiber is one formed from a strip of polymer material, such as is sold under the trade name Mylar.

Yet a further preferred cross-section can be a D_shaped cross-section, with the light emission surface being on the flat side of the D. Normally the fiber will be bent in the plane of the flat side. Other cross-sections and arrangements can be provided.

The invention includes, in a vehicle suspension system which includes an electronic system for sensing displacement between a vehicle body or frame and a vehicle wheel system and comprises a suspension sensor, the improvement comprising a flexible beam and a fiber optic curvature and displacement sensor mounted to the flexible beam, the sensor comprising a fiber optic light guide having at least one light emission surface extending, for part of the length of the guide, in a direction selected from: a substantially circumferential direction, and a substantially curved axial direction when in a curved portion of a curved guide.

The invention also includes a method of sensing curvature and displacement, of an elongate member, comprising attaching a fiber optic light guide to the member, the light guide having a light emission surface extending, for part of the length of the guide, in a direction selected from: a substantially peripheral direction, and a substantially curved axial direction when in a curved portion of a curved guide, the light guide extending along the member; injecting a light beam into one end of the light guide, detecting the light beam at the other end of the light guide, measuring the difference in the light beam between the one end and the other end, indicating curvature or displacement, of the member.

Preferably the method includes selecting the light guide so as to optimize sensing of curvatures over a range that includes, as a substantial portion of the total substantially linear range sensed, curvatures that produce increasing transmission of light with increasing curvature.

Preferably the method includes attaching a plurality of fiber optic light guides to the elongate member, each having a plurality of light emission surfaces such that the planes of maximum sensitivity of the guides are at different angles from each other so that at least one guide maximally indicates curvature at a unique planar inclination.

A preferred arrangement may utilize two to six fiber optic light guides oriented in different directions at predetermined angles relative to each other.

19

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be readily understood by the following description of certain embodiments, by way of example, in conjunction with the accompanying drawings, in which:

Figure 1 is a diagrammatic illustration of a bending sensor apparatus, with the sensor shown cemented to a bending beam;

Figure 2 is a cross-section through an optical fiber in accordance with the present invention;

Figure 3 is a cross-section similar to that of Figure 2, illustrating a modification thereof;

Figure 4 is a perspective view, on a large scale, of part of a light guide showing a form of surface treatment;

Figure 5 is a side elevation of the light guide of Figure 4;

Figure 6 is a transverse cross-section of the sensor as on line X-X in Figure 5;

Figure 7 illustrates an alternate form of surface treatment of the light guide;

Figure 8 is a side elevation of the light guide of Figure 7;

Figure 9 is a transverse cross-section of the sensor as on line Y-Y of Figure 8;

20

Figure 10 is a transverse cross-section of a sensor showing the axes of maximum and minimum sensitivity to bends;

Figure 11 is a perspective view of a sensor employing a non emitting reference fiber paired with an emitting, sensing, fiber;

Figure 12 is a perspective view of a triple sensor for detecting the three-dimensional bend vector;

Figure 13 is a cross-sectional view of the triple sensor on the line Z-Z of Figure 12, showing the 120° arrangement of emitting sections;

Figure 14 is a schematic diagram showing light paths and electronic circuitry;

Figure 15 shows an alternative form of the light guide return path;

Figure 16 shows an alternate application of the sensor, to measurement of position;

Figure 17, 18 and 19 are graphs of the percentage changes in transmission of light guides treated in various ways to sense bending;

Figures 20 and 21 are graphs of the percentage changes in transmission for an opposed sensor pair made from two light guides;

Figure 22A is a side view of a fiber with alternating bands of treated and untreated material;

21

Figure 22B is a cross section through one of the untreated portions of the fiber in Figure 22A;

Figure 22C is a cross section through a treated portion of the fiber in Figure 22A;

Figure 23A is a side view of another type of treatment, showing alternating bands of treated and untreated material, the treatment not encompassing the entire circumference of the fiber.

Figure 23B is a cross section through one of the untreated portions of the fiber in Figure 23A;

Figure 23C is a cross section through one of the treated portions of the fiber in Figure 23A;

Figure 23D is a cross section through a fiber as in Figure 23A, but treated in an alternate manner;

Figure 24A is a longitudinal cross section of a straight section of fiber with three emission surfaces as in Figure 23A, showing ranges of light rays subtended by emission surfaces;

Figure 24B is a longitudinal cross section of a downward curving fiber as in Figure 24A;

Figure 24C is a longitudinal cross section of a upwardly curving fiber as in Figure 24A;

Figure 25 shows a family of curves showing light loss through a fiber treated with successively more emission surfaces, as it is bent over a wide range of curvatures;

22

Figure 26 shows a more detailed graph of a fiber sensor treated as in Figure 25, to have a linear region centred on zero curvature as well as data from another type of sensor;

Figure 27 shows a sensor system including a loop of fiber used to return light to the optoelectronic measuring system. The loop is treated to act as a sensor and is mounted to a bending beam to measure curvature near the end of the beam;

Figure 28A is a longitudinal section of the loop in Figure 27. The top portion of part of the cladding in the loop has been removed to allow light to escape in two patches on a side of the fiber. The patches are located on curved portions of the loop;

Figure 28B is a plan view of the fiber in Figure 28A;

Figure 28C is a cross section through one of the treated portions of the fiber in Figure 28A;

Figure 28D is a cross section through one of the untreated portions of the fiber in Figure 28A;

Figure 28E is a cross section through a treated portion of another embodiment like the fiber shown in Figure 28A except that both sides of the loop have been treated;

Figure 28F is a cross section through a treated portion of another embodiment like the fiber shown in Figure 28A except that the treated portion is located on the inner portion of the loop and is in a substantially circumferential orientation;

23

Figure 28G is a plan view as in Figure 28B, except that the emission surface is continuous;

Figure 29A shows a plan view of a turnaround loop as in the embodiments portrayed in Figures 28A through 28G. Two rays which originate as rays in the plane of the loop are shown travelling through the fiber, remaining in the said plane;

Figure 29B shows a cross section through the fiber just before it begins to bend, showing the two rays still in the said plane;

Figure 29C shows a cross section through the fiber at the centre of the loop, showing the position of the two rays, which are still in the said plane;

Figure 30A shows the same loop as in Figure 29A but with a ray that is parallel to the plane of the loop but displaced vertically;

Figure 30B shows a section through the fiber just before it begins to bend, showing the position of the ray above the plane of the loop;

Figure 30C shows a section through the fiber, containing the ray, showing deflection of the ray downward as it refracts from the outer wall of the loop;

Figure 30D shows another section of the fiber, containing the ray, showing deflection of the ray again downward, at such an angle that it is lost from the fiber at the outer wall of the loop;

24

Figure 30E shows sensor loss due to curvature for a fiber loop with two emission surfaces, and for a similarly treated straight section of fiber;

Figure 31A is a plan view of a loop treated to sense curvature of a diaphragm, attached along the surface of a diaphragm;

Figure 31B is an elevation view of the sensor of Figure 31A;

Figure 32A is a plan view of a sensor as in 31A, except the loop is supported in a curve from above the diaphragm and touches the diaphragm at a point, so as to sense displacement of the diaphragm;

Figure 32B is an elevation view of the sensor system of Figure 32A;

Figure 33A is a plan view of a loop treated to sense curvature, attached at its apex to a rotating drum or shaft, for the purpose of indicating position of the shaft according to a varying curvature imposed on the loop;

Figure 33B is an elevation view of the sensor structure of Figure 33A;

Figure 34 is a transparent view of a joystick input device containing loops of fiber treated and arranged to sense displacement of the flexible joystick handle in two degrees of freedom;

Figure 35A is a plan view of a loop treated to sense curvature, mounted as a cantilever beam for sensing vibration and acceleration;

25

Figure 35B is an elevation view of the sensor of Figure 35A;

Figure 36 is a side view of a spring and fiber loop system designed to translate large displacements of a body into relatively smaller displacements of the end of the loop;

Figure 37 is a schematic diagram showing light paths and electronic circuitry;

Figure 38A is a perspective view of one form of a rectangular cross-section strip form of sensor;

Figure 38B illustrates the sensing deflection of the sensor of Figure 38A;

Figure 39A is a perspective view of an alternative form of a rectangular cross-section strip;

Figure 39B illustrates the sensing deflection of the sensor in Figure 39A;

Figure 39C is a side view of the sensor in Figure 39A;

Figure 40A is a perspective view of a sensor having a D-shaped cross-section;

Figure 40B is a cross-section of the sensor of Figure 40A.

Figure 41 is a plan view of an alternative form of a rectangular cross-section strip;

26

Figure 41' is a graph of light transmission through a loop sensor made of light guide with a rectangular cross-section; and

Figure 42 illustrates a means of attachment useful in sensing angular displacement.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figures 1 to 21, illustrate various forms of sensors, associated electronic circuitry and output curves as claimed in above-mentioned Application Serial No. 07/915,283.

Figure 1 illustrates a bending sensor 10 mounted with adhesive on bent beam 11. In the example, light is conveyed from a photo-emitter 12 through a plastic or other optical fiber light guide 13 to the sensor portion 10, and thence through guide 14 to a photo-detector 15. The light guide near the sensor region 10 has had its outer protective jacket removed, and the light conducting core exposed along a strip on the surface; portions 13 and 14 leading to the sensor region may have the jacket in place. The sensing portion 10 is adapted to sense bending. The photo-emitter 12 and photo-detector 15 are part of an electronic measuring system 16 and display 17.

Figure 2 illustrates, in cross-section a conventional optical fiber wave guide 18 having a light conducting fiber 19 and a cladding 20. Normally there will be a buffer layer and a coating layer also. The cladding is removed locally, at 21, extending in a band along the fiber 19, to form a light emitting surface 22. The band can be formed by deliberately removing cladding as by abrasion, melting, etc. or by displacement as by pressure or rubbing on the fiber,

27

for example by a heated tool, depending upon the particular form of fiber.

Figure 3 illustrates a modification of the arrangement of Figure 2, in which the light emitting surface band 21 is covered with a light absorbent material 20a. Typical materials for the coating 20a are graphite filled epoxy resin, dye-filled resins and similar materials. The use of the coating 20a prevents emitted light interfering with any other instrument or structure and also prevents any back reflection into the fiber, which would affect the measure- ments. The additional coating 20a can be applied only over the band 21, but more commonly is applied around the entire fiber.

Figures 4, 5 and 6 illustrate one example of a fiber 19 with the emitting surface textured. Serration 23 have been created on one side of the fiber, as by pressing it onto the surface of a file. Similar serration can be created by heat forming and molding. Both plastic and glass optical fibers can be so formed. Heat forming can be accomplished by pressing the fiber slightly onto a heated metal surface which can be serrated, corrugated, or otherwise formed. The angle of the serration can vary. It is not necessary to first remove the cladding of the fiber as this will be displaced. After treatment, a sensor portion emits some light along the length while transmitting a portion of any light within it to either end.

Figures 7, 8 and 9 illustrate another form of serration of a fiber 19. In this example the wedge-shaped serration 23 of the sensing portion 10 are separated by small spaces 24. The exact shape of the

serration can vary considerably. Diamond-shaped
serration have also been successfully used. These are
formed by pressing the fiber against a file with a
pattern of intersecting serrations.

Alternatively, one side of the fiber can be
abraded by sanding, sand-blasting, etching, or other
means of removing or changing the cladding layer.

Figure 10 illustrates the axes of maximum and
minimum sensitivity, and the direction of signal
change of a bending sensor. In this cross-section,
the light emitting surface band is 22 at the top of
the sensing section of the fiber. Bends within the
vertical plane containing A-A produce the maximum
change in transmission of light through the fiber.
Thus A-A is called the axis of maximum sensitivity.
For bends concave upward, the transmission increases.
For bends concave downward, the transmission
decreases. The minimum change in transmission occurs
for bends in the horizontal plane containing B-B.
Bends in this plane produce negligible change in
transmitted light, so B-B is called the axis of
minimum sensitivity. Intermediate response occurs for
bends off the major axes, such as at C-C. This
intermediate response is a cosine function of the
angle between the plane of maximum sensitivity and the
plane of the angle of the bend. In the figure, + and
- signs have been placed to indicate increases and
decreases in transmitted light relative to the
transmission of the fiber when it is straight. The
surface band 22 can be just bare fiber, as in Figure
2, or textured, as, for example, in Figures 4 to 9.

Figure 11 illustrates a sensor including a paired
reference fiber. Fiber 19 has a sensing portion 10.

Fiber 25 has no sensing portion. The pair are used in
dual detection methods, where all measurements are
referenced to the transmission through fiber 25.
Because fiber 25 is arranged mechanically in the same
way as fiber 19, most errors are eliminated from the
measurement, by virtue of the fact that untreated
fibers show little change in transmission for small
bend angles (roughly less than 20°, whereas formed
fibers are optimized for response to bending).

Figure 12 illustrates three fibers, arranged to
form a sensing system capable of detecting the three-
dimensional vector describing the applied bend. Each
fiber has a light emission portion 10, just bare fiber
or formed with serration or abrasions. The sensing
portions are arranged so that the axes of maximum
sensitivity are at 120° to each other. Figure 13
shows this relationship more clearly. Solving
simultaneous equations for the magnitude and sign of
the transmissions of the fibers will yield the three
components of the bend vector of an element, such as
a beam, to which the sensor has been affixed.
Alternate arrangements of the fibers are possible,
such as having the sensing portions facing at
different angles, triangular rather than flat bundles,
or having the fibers separated from one another. In
the examples illustrated in Figures 11, 12 and 13, the
fibers are conventional in that they are composed of
the main fiber, of glass, plastic or other, with a
cladding layer. The cladding layer is locally removed
at the sensor positions 10 as mentioned above, by
various means.

Figure 14 illustrates one simple example of
electronic circuitry that can be used to measure the
transmission of light through a paired sensor element

such as that shown in Figure 11. In Figure 14, fiber
19 (shown coiled to indicate arbitrary placement and
length of the guide conveying light to and from the
sensing portion) has the light emitting strip at 10.
Fiber 25, which is otherwise the same as fiber 19, has
no sensing portion at position 26, which represents a
section of the fiber in close proximity to sensor
section 10.   Both fibers are illuminated by
photoemitters E1 and E2, which are light emitting
diodes. Photodetectors D1 and D2, which receive light
from the fibers, are PIN photodiodes, back-biased with
12 Volts to enhance the speed of their response to
light energy.   U1 and U2 are high input impedance
operational amplifiers arranged as transimpedance
amplifiers, converting light energy linearly into
voltages fed to the inputs of U3, which is an
operational amplifier connected as a differential
amplifier with a gain of 10. The gain of amplifier U2
can be varied with R1 so that for a straight fiber,
the inputs to U3 are equal. In this condition, the
optoelectronic circuit is analogous to a two-armed
bridge such as is used to make strain-gauge
measurements.   Errors due to degradations in the
fibers, connector variations, temperature
fluctuations, and the like tend to cancel before
reaching the output of U3. The output of U3 is a
voltage which aries with bending at the band portion
10. The output voltage can be further amplified and
sent to a display unit or used to control various
parameters, such as actuators designed to minimize the
angle of bend.

Many variations of the circuitry are possible,
including variations with much greater immunity to
error sources. One such variation would use the same
light source and detector, separating the signals by

chopping them at different frequencies and employing
synchronous detection.   Another variation is to
replace U3 in Figure 14 with a divider circuit, so
that the sensor signal is divided arithmetically by
the reference signal.

Another variation uses one photoemitter, for
example E1 in Figure 14, to illuminate the sensor
fiber, such as 19 in Figure 14, and also to illuminate
a reference fiber such as 25 in Figure 14. This last
variation may be further enhanced by eliminating U3,
using U2 and another amplifier to control the light
out of 25 to constant value, and reading relative
light transmission through 19 directly from the output
12.

Figure 15 illustrates a variation of the sensor
design which eliminates loops of light guide past the
sensing portion. Light from a photo-emitter enters
the system through guide 19 and passes through the
sensing portion 10. Another sensing portion 27 faces
sensing portion 28 on guide 29. An opaque cap 30
filled with optically clear adhesive 31, covers this
junction area.   Guide 29 carries light back to a
photo-detector. The junction region at 27 and 28 is
held rigidly by the cap and adhesive so that it does
not respond to bending. This arrangement allows the
use of parallel fibers without return loops, which can
be an advantage when embedding the sensors in long,
narrow structures.

Alternatively, the fibers 27 and 28 can be non-
serrated, and inserted part way into the opaque cap
30, in this variation, the cap is preferably filled
with translucent white polymer such as epoxy mixed
with white pigment. Diffusion of light through the

32

polymer accounts for transmission of light from fiber
27 to fiber 28.

Alternatively, a mirror can be used to reflect
light from the distal end of the sensor fiber back
into a return fiber.   In another alternative, a
directional coupler can be used with a single sensor
fiber which has a mirror mounted at its distal end.
The coupler is used to pass light to the proximal end
of the fiber from the emitter, and to direct reflected
light emanating from the proximal end of the fiber,
into the detector. Typically, the directional coupler
would be placed between the emitter, the detector, and
the proximal end of the fiber.

Figure 16 illustrates the application of the
bending sensor to the measurement of displacement.
Vertical displacement 32 between blocks 33 and 34
(representing, for example, moving parts of a
mechanical system), is measured by a bend-sensing
region 10 in guide 19, cemented into flexible beam 35,
which is attached to the two blocks.   Similar
fixturing, with or without a flexible beam, would
enable the measurement of angles, such as pedal
position, over a large range.

The advantages of the sensing devices described
above are illustrated in Figures 17, 18 and 19. For
these figures the sensors were fabricated from methyl
methacrylate optical fiber, 1 mm in diameter.   The
black plastic jacket was left on the fiber except for
a 50 mm section near the sensing portion, where the
black plastic was removed.

Figure 17 illustrates, by way of example, the
percentage change in transmission, that is the amount

33

of light transmitted compared to 100 percent for a
straight fiber, of a 1 mm diameter plastic fiber
formed over a 25 mm length with serration and affixed
with epoxy adhesive to a plastic beam. Weights were
placed on the beam, which was clamped at one end, to
produce the angular deflections shown on the
horizontal axis of the graph. Two outputs of the
sensor are shown. One is from the sensor when the
beam is mounted to bend along the axis of maximum
sensitivity (serration pointing up); the other is the
output when the beam is mounted to bend along the axis
of minimum sensitivity (serration pointing
horizontally). There is virtually no sensitivity to
bending along the axis of minimum sensitivity. The
sensor response in the axis of maximum sensitivity is
essentially linear with respect to angular deflection,
increasing for upward bends and decreasing for
downward bends.

The graph illustrates the sensitivity obtainable
with very simple electronics (for example, as shown in
Figure 14). One could measure beam deflection with a
strain gauge on the top of the beam. The strain gauge
would be responding to elongation of the top surface
of the beam rather than curvature of the top surface.
The beam is undergoing an elongation of approximately
120 microstrain (microns per meter) along its top for
a 3˚ deflection, indicating that the optical sensor is
achieving a resolution of better than 12 microstrain
(120 microstrain over 10 data points) for this
experiment. Other sensors have been constructed which
are capable of resolving less than 1 microstrain,
which is the approximate lower sensitivity limit for
strain gauges. Because it is possible to measure
curvature with a bending sensor on the neutral axis of

34

the beam, where there is, by definition, no strain,
the lower limit for strain sensitivity is zero.

Figure 18 illustrates, by way of example, the
response of a fiber light guide having serration over
a 25 mm length compared to the response of an unformed
fiber. The fibers were clamped near one end of the
sensitive region and moved so as to bend in a loose
curve of the total angle shown on the horizontal axis
of the graph. The fiber with the sensing portion was
moved in the plane of maximum sensitivity. The fiber
demonstrates a large range of linear response;
approximately ±20°. When moved similarly, the
unformed fiber, an example of a microbend sensor,
showed virtually no change with angle, except for
angles over 20 degrees, where the response is
approximately 20 times less than the formed fiber.

Figure 19 illustrates, by way of example, the
response of three fibers having the textured surface
formed in different ways. The test setup is the same
as for Figure 17. The first fiber has serration over
a 25 mm length. The second is formed by abrading
slightly with fine sandpaper around the circumference
of the fiber over a 25 mm length. The third is formed
by abrading slightly with the same sandpaper over a 25
mm length, but only on one side of the fiber, similar
in overall shape to the region of serration of the
first fiber. The two fibers having the textured
surface on one side show good preservation of
direction of the bend in their responses. The fiber
having the textured surface on its entire surface
shows no preservation of the direction of bend. It
would have to be bent when mounted on a structure.
The serrated fiber shows linearity of response over a
wider range than the fiber sanded on one side.

35

Figure 20 illustrates, by way of example, the response of a sensor pair mounted with epoxy adhesive inside a small piece of plastic tubing. Each sensor was formed by removing cladding along a strip on the side of a silica fiber core, 200 microns in diameter. The strip was 10 mm long. The two strips were coated with graphite-filled epoxy and arranged to face in opposite directions, so that response to bends was of opposite polarity but approximately equal magnitude for each sensor. The "percentage change in transmission" shown in Figure 20 refers to the difference in the two electrical signals resulting from light transmission changes in the two sensors, as a percentage of the electrical signal from one sensor at rest. This paired method of measurement is one means of greatly decreasing the effects of common-mode emitter and detector drift. In this example, the tubing was first bent, by means of a micrometer drive, upward in the plane of maximum sensitivity (positive horizontal graph axis), away from its rest position (zero on horizontal axis). Next it was moved back toward its rest position. These steps were repeated for downward bends. The data points in Figure 20 illustrate the excellent linearity of the system, and the low hysteresis ("away from zero" and "toward zero" points are nearly coincident). A straight line (Linear Fit") has been drawn on Figure 20 to illustrate the excellent linearity of response.

Figure 21 shows the same data points as Figure 20, over a small range of bends near the origin.

Figures 22 to 42 illustrate further embodiments in accordance with the present invention.

36

Figure 22A illustrates a fiber 38 with alternating circumferential bands of treated material 39 and untreated material 40. The figure shows the layers of the fiber out to the level of the cladding 43. The bands are formed by modifying the core and or cladding so that light is lost from the core. The bands can be formed by deliberately removing cladding as by abrasion, melting, etc. or by displacement as by pressure or rubbing on the fiber, for example by a heated tool, depending on the particular form of fiber. The treated bands are covered over with light absorbing material 41 which provides mechanical strength and environmental protection where cladding has been modified, but whose primary purpose is to absorb all light exiting the fiber from the core 42, which is shown in Figures 22B and 22C. Without this layer, the fiber can still act as a light guide because air surrounding it will have an index of refraction lower than that of the core. The fiber may actually transmit more light if the cladding is removed and no light absorbing coating is applied, thus preventing it from properly measuring curvature. In any case, without an absorbing coating the fiber will exhibit a nonlinear response that varies over time, especially if reflective materials, liquids, and dirt are present. With absorbing coating the response of the fiber is very constant over time and is unaffected by environmental factors. The absorbing coating may consist of carbon-filled epoxy, dyed elastomer, carbon-filled hot glue, or any other substance that permits light to exit the fiber but prevents it from re-entering in any substantial quantity. The light absorbing coating may serve other functions as well, such as protection of the fiber against environmental contamination. It may be applied only to the sensor portion of the fiber or may

37

be incorporated into a part, such as a rubber or graphite/epoxy part, into which the sensor is embedded.

Figure 22B is a cross section of fiber 28 through X-X where no treatment has been performed. Cladding layer 43 covers core material 42. Little light can escape from this section because the index of refraction of the cladding is less than that of the core. Excess absorbing material (not shown in this figure) may for convenience or for structural reasons cover the cladding in any of the untreated portions of the fiber.

Figure 22C illustrates a cross section of the fiber 38 through Y-Y, a treated portion. Where the cladding has been removed or modified, it is replaced by absorbent material 41, which covers the core 42 and any remaining cladding (not shown in this figure).

Figure 23A illustrates a fiber 44 with cladding 43, that has been treated as in Figure 2A except that the treated portions 45 cover a partial extent of the circumference.

Figure 23B shows a cross section through Z-Z, an untreated portion of fiber 44. This untreated portion is identical to that in Figure 2B and includes a core 42 and a cladding 43.

Figure 23C shows a cross section through P-P, a treated portion of fiber 44. The cladding has been modified or removed over part of the circumference and back filled with light absorbing material 41.

38

Figure 23D is a cross section through a fiber treated like the fiber in Figure 23A but with both upper and lower surfaces treated to emit and absorb light. Although it is treated on both sides, it too will be maximally responsive to bends in the plane of maximum sensitivity passing through the centres of the two treated arcs. Its response to bends outside this plane will be a cosine function of the angle between the plane of maximum sensitivity and the other plane.

This cosine law is what allows the use of multiple sensor fibers with different angles of planes of maximum sensitivity to that three dimensional bands can be resolved by a set of sensors. It applies to any of these sensors except ones that include bands or rings which extend the entire circumference. The best cosine effect happens if up to half the circumference is treated to form a band. Otherwise, there is a "DC offset" added to all the cosine responses up to the point that the signal does not change with different plane angles – this happens when the bands are completely circumferential in extent.

Figure 24A shows in longitudinal cross section a cone of light with an angle Ct that represents the solid angle of light that meets the internal refraction criteria for a fiber such as fiber 44 in Figure 23A. This angle is called the acceptance angle of the fiber. The size of Ct is determined by the relationship between the indices of refraction of the core and cladding.

The acceptance angle can be related to the indices of the core and cladding through

$$Ct = 2 \sin^{-1} ((n_1^2 - n_2^2)^{1/2}),$$

where the argument of the inverse sin function is called the numerical aperture of the fiber, which is determined from the index n_1 and n_2 of the core and cladding respectively. Rays leaving representative point 46 with angles included in Ct will be refracted back into the core wherever they strike the cladding, and continue propagating down the fiber. Rays within angular ranges C1, C2, and C3 will strike the treated portions 41 and be lost.

Figure 24B shows angular ranges C4 and C5 within total cone angle Ct for the fiber 44 in a bent state. Because of the bend, the treated portions subtend smaller angles of light, so that C4 < C1, C5 < C2, and there is no C6 corresponding to C3 in Figure 23D. This is the mechanism which produces an increase in light level as the fiber is bent to make the treated portions become more concave. Conversely, as it is bent in the other direction, the angles subtended by the treated portions become larger and represent a larger portion of the total acceptance angle Ct. This causes a loss of light compared to a straight fiber.

It is possible to increase the range of curvatures over which the fiber will have a substantial change in throughput for bends making the treated portions more concave. This can be done by adjusting the axial lengths of the individual light emission surfaces and the length of the entire treated zone. Figure 25 shows the results of tests of a fiber treated with successively more emission surfaces along an axial line of the surface of the fiber. Each surface was 3mm long, and spaced from the others axially by 3mm. Data are shown for 2, 4, 6, and 8 emission surfaces. The fiber was held over various round mandrels to produce the curvatures shown.

40

Curvatures include positive (emission surfaces
concave) and negative (emission surfaces convex)
values. From the family of curves in Figure 25 it is
evident that when there are fewer surfaces, the
positive curvatures tend to produce changes in light
that are not linear with curvature, but the negative
curvatures tend to produce linear changes. This
effect is very evident in the 2 x 3mm curve. As more
surfaces are added, the linear portion of the curve
moves toward the positive curvature region, as in the
8 x 3mm curve. Intermediate values (as in the 6 x 3mm
curve) can be chosen to place the linear range
approximately intermediate between positive and
negative curvatures.

Figure 26 shows a more detailed graph of a fiber
sensor treated as in Figure 25 to have a linear region
centred on zero curvature, as well as data from
another type of sensor. The "centred" data are shown
in the curve for "Treatment 1." The data for
"Treatment 2" are from a similar fiber that was
treated over its entire circumference so that it has
a negative sloped response for positive curvatures.

Together, Figures 25 and 26 show that by applying
various methods of treatment, it is possible to place
the linear ranges of the fiber response curves so that
they reflect various ranges of curvature, and to
change the slope of curvature over a wide range.

The various curves shown in Figure 25 are
explained in the following way:
        For a fiber bent so as to make its emission
        surfaces more convex, (negative curvature in
        Figure 25), the surfaces continue to intercept
        more rays the farther the fiber is bent. The

41

fiber may be bent substantially in this direction
with an ever increasing loss of light. However,
the fiber will have a nonlinear response for very
large negative curvatures (as seen in Figure 25,
8 x3mm), because of the failure of the emission
zones to intercept additional rays. As the fiber
is bent the positive way, fewer rays are
intercepted (see Figure 24C) as the bands take on
an increasingly concave form. However, for a
short emission surface, the surface is soon
substantially out of the path of the rays. There
is then no further loss of light, because it is
predominantly reflected from the side of the
fiber away from the emission surfaces, and does
not interact with them. The interaction is least
when there are few emission surfaces, as
evidenced in Figure 25, 2 x 3mm and 4 x 3mm. The
2-surface fiber (and a 1x3mm surface fiber which
is not shown) even shows an increased loss for
the largest curvature tested, probably due to
microbending losses predominating over emission
surface losses.

In one embodiment, the present invention utilizes
such a large linear region for positive curvatures to
increase the net throughput of the sensor system. By
spacing the emission surfaces, it is possible to both
increase the sensitivity and size of the linear region
for positive curvatures and to minimize the residual
light loss because a substantial number of rays can
still pass the sensor region without attenuation. The
extended structure permits distant bands to intercept
light rays that are nearly parallel to the fiber axis,
even when the curvature change is minimal. This leads
to a high sensitivity with minimum residual light
loss. If one attempts to achieve high sensitivity for

42

positive curvatures by lengthening a single emission surface, a limit is reached where the increase in residual light loss exceeds any gains in sensitivity, even though linearity is maintained.

For 1 mm plastic fibers, typical light emission surfaces for efficient sensors are approximately 2 to 10 millimetres in length, spaced by 2 to 10 millimetres. The overall length depends on the desired range but is typically up to 50 cm. Surfaces for smaller glass or plastic fibers are typically smaller. Notches may be used, but will not achieve the same sensitivity as uniform surfaces with smaller surface texture dimensions. This is probably because notches perform an emission function but also tend to scatter light back into the fiber. This is particularly true if they are not covered with a light absorbing layer. Notches have the further disadvantage of weakening the fiber.

If the emission surfaces occupy the total circumference of the fiber as in Figure 22A, there is no increase in throughput for bends of the fiber in any plane. All of the sensing is done through decreases in light level. Nevertheless, spaced emission surfaces are still an advantage for many sensors, as they can be used to sense average curvature over a greater axial length of the fiber. This can eliminate or reduce undesirable effects from large local changes in curvature, for instance due to the presence of a foreign body under the fiber.

Ordinarily, a loop is used to return the light signal to the optoelectronic measuring system. Often, space is limited so that the loop must be formed in a tight curve such that substantial amount of light is

43

lost from its outer convex surface. When combined with the residual light loss of a sensor elsewhere on the fiber, the resulting total light loss may be excessive. The "loop sensor embodiment" is designed to reduce this total loss by placing the emission surfaces in a novel manner.

In Figure 27 is shown a sensor system designed to have maximum throughput even though it includes a loop 48 at the end that may be in a tight curve that loses light at its convex outer surface. This figure includes the same components as in Figure 1 except that the treated section 10 is on the loop 48 instead of on a straight section of the fiber. The sensor is designed to measure curvature of the substrate to which the loop is attached. In Figure 27, the sensor would be used to measure curvature at the end of the beam 11.

A detailed drawing of one embodiment of the sensor of Figure 27 is shown in Figures 28A through 28F. In Figure 28A, the loop is shown in longitudinal section. Emission surfaces 49 have been formed in one surface of the fiber by removing cladding 51 from core 50 and replacing it with light absorbing material 41. In Figure 28B, the emission surfaces 49 are shown in plan view. Cross sections in Figure 28C and Figure 28D show sections through treated (D-D) and untreated (E-E) portions of the fiber respectively. The number of emission surfaces is representative only. Larger loops could contain more emission surfaces. Emission surfaces may be formed on surfaces above or below the plane of the loop, or on an inside or concave portion of the curvature of the loop. Figure 28E is a cross section illustrating emission surfaces on both the upper and lower surfaces of the loop. Figure 28F is a

cross section illustrating an emission surface on the inner concave portion of the loop. Figure 28G shows another variation of loop sensor wherein the emission surface 49 covers virtually all of the upper surface of the loop.

Figure 29A shows the core 30 of the loop of Figures 28A through 28D. Rays h1 and h2 are in the plane of the loop. They meet the outer convex surface of the loop and are refracted around the loop to continue on through the fiber. For rays substantially in this plane, there will be little change in direction out of the plane as they traverse the loop.

Figure 30B shows a ray v1 that is substantially out of the plane of the loop but parallel to it. The ray is shown in Figure 30B, a vertical (perpendicular to the page) cross section through A-A, just before the ray enters the curve of the loop. The ray impinges on the outer convex surface of the loop. Figure 30C shows a vertical section through the core containing the ray v1 after it refracts from this first collision. Because it is substantially above the plane of the loop, it is deflected downward by the curve of the fiber and collides a second time with the wall of the core. Figure 30D shows a vertical cross section through C-C, a plane containing the ray v1 after its second collision. It is now travelling even more downward and impacts the outer curve of the loop at an angle such that it cannot be refracted back into the fiber, but travels through the cladding (not shown) and is lost.

Thus, rays that are travelling out of the plane of the loop but parallel to it will be deflected vertically as they travel through the loop. Rays

45

above the plane will be deflected downward.   Rays
below the plane will be deflected upward.   If they are
sufficiently above or below the plane, they end up
being lost because they strike the core/cladding
boundary at too small an angle of incidence to the
normal due to the quasi-spiral reflections indicated
in Figures 30A through 30D.

We have seen above that there is a vertical
impetus imparted to rays that travel through the loop
without being lost at the outer convex surface of the
loop.   For convenience, these rays will be called
"survivor" rays.   They are distinct from "doomed" rays
described Figures 30A through 30D that will either
impinge directly on the emission surfaces early in
their travel through the loop or be lost to the outer
surface through excessive deflection.   This change in
elevation causes them to interact more or less with
emission surfaces near the top or bottom of the loop.
Thus, as the loop is curved out of its plane by an
external stimulus, the emission surfaces interact with
the survivor rays and cause the throughput to vary
with curvature in much the same way as it does if the
emission surface is located in a straight portion of
the fiber.   By adjusting the length, spacing, and
circumferential extent of the emission surfaces, it is
possible to change the throughput so that it is linear
with curvature and to adjust the midpoint of the
linear range so that it includes the zero curvature
point.

With the sensor on the loop, the emission
surfaces can be adjusted so that a large proportion of
the survivor rays interact with the emission surfaces.
Those survivor rays that do not get absorbed by the
treated emission surfaces for certain curvatures are

46

by definition the rays that get through the loop.
This leads to a high sensitivity of survivor rays to
curvature. Survivor rays are made up predominantly of
rays that enter the loop in planes near the horizontal
(in the paper) plane of the loop and that have small
vertical components. By contrast, "doomed" rays
arrive in predominantly vertical planes with larger
vertical components. If instead of placing the
emission surfaces on the curved loop, we placed them
on the relatively straight fiber nearby, rays
containing most of the sensor information would be in
the vertical plane as they enter the loop and thus
would be doomed rays. This would result in the light
exiting the loop being made up mostly of rays that
have not been modulated by the sensor. This is
equivalent to reducing the sensitivity of the sensor.
The same argument holds for a sensor downstream of the
loop. The light leaving an untreated loop has been
stripped of most of its vertical modes, so that a
sensor placed in this light stream will be modulating
a minority portion of the light passing through it.
However, it is possible to form a useful loop sensor
wherein the emission surfaces extend somewhat beyond
the loop, as long as they are substantially on the
loop.

Although the loop sensor embodiment has
advantages of increased sensitivity and lower residual
light loss for many arrangements of emission surfaces,
this should not be taken to be its only advantage.
Even in the absence of sensitivity and loss
advantages, there are compelling reasons to form a
sensor on the loop. These include sensing at the end
of a structure, reduction of fiber length, ease of
mounting, reduction of stresses on the fiber inherent
in mounting a sensor portion and a loop portion

47

separately with free fiber in between, ease of manufacture, preservation of orientation, and simplicity. In addition, loop sensors may be made to be relatively free from responses to bends within the plane of the loop.

The upper curve in Figure 30E shows the output of a loop sensor made by forming two axially oriented emission surfaces on the surface of a 7 mm diameter fiber loop of 1 mm diameter plastic fiber. The lower curve shows the sensor output when the same patches are formed on a straight section of fiber 2 cm from a 7 mm diameter untreated loop. For this arrangement of emission surfaces, the output of the loop sensor is superior to the output of a sensor formed apart from the loop.

Figure 31A shows another embodiment of the loop sensor, wherein a fiber 51, treated at the loop 52 to sense bending of the plane of the loop, is attached to a flexible diaphragm 53. These same parts are shown in Figure 31B. As the curvature of the diaphragm 53 changes, the output of the sensor changes. This sensor structure could be used to measure pressure or to form a membrane-type keyboard, or to perform many other tasks wherein a diaphragm undergoes changes in curvature.

Figures 32A and 32B show a sensor and diaphragm as in Figures 31A and 31B, wherein the fiber 51 is held in a fixed support block 57 so that at least the sensor portion of the fiber changes curvature according to the displacement of the diaphragm 53 at the point of attachment or contact 62.

48

Figure 33A shows a loop sensor wherein fiber 51 is treated at multiple portions 54 to be sensitive to bending of the plane of the loop. At the apex of the loop, it is attached to a turning shaft 55. Figure 33B shows an elevation of the same sensor structure, wherein it can be seen that the turning shaft can be turned over a limited angular range clockwise or counterclockwise about pivot 56 and that the loop is attached to an anchor point 57. As the loop winds around the shaft, its curvature increases, changing the throughput of light.

Figure 34 represents a joystick device wherein two loop sensors 58 and 59 are embedded in a vertical flexible shaft 60, attached to a base 61. The loops have planes of maximum sensitivity at right angles to each other, centred about the centre of the shaft. The outputs of the fiber sensors represent orthogonal components of the curvature of the shaft. In a miniaturized form, this sensor could be a keyboard-mounted input device for a computer.

Figures 35A and 35B portray a loop sensor consisting of fiber 51 held by fixed support 57, with a sensor zone 52 on the loop. The structure to the right of the support 57 forms a cantilever beam. It is used to sense acceleration or vibration perpendicular to the plane of the loop. Optionally, a mass 63 may be attached near the end of the structure to modify the dynamic response of the sensor. The sensor could be used to perform a wide variety of acceleration measurements, including measurement of impact deceleration for the purpose of deploying an airbag protective system for automobiles. This structure is amenable to being manufactured by micromachining of a semi-conductor or glassy

substrate, wherein the fiber would be formed from the
substrate and undercut by an etching process. A thin
web or plate affixed to one side of the loop (not
shown) could be added to prevent the shape of the loop
from changing within its plane.

Figure 36 portrays a displacement sensor using a
loop sensor 68 consisting of a fiber 51 with a treated
portion 52 on a loop at its distal extent, attached to
a spring at pivot point 64. The sensor is designed to
sense a large displacement 67 of structure 66 relative
to structure 65, which is fixed to a frame of
reference to which the fiber is also fixed, both by
means of holding structures 57. By selecting the
attachment point of pivot point 64, the movement of
the end of the sensor is restricted to a smaller range
than movement range 67. The fractional amount of
reduction is according to the ratio of distance X2 to
the total of distances X1 and X2, yet the reduced
movement is linearly related to the movement of
structure 66. The pivot point may take the form of a
hinge, ball joint, flexible beam, cable, wire,
elastomer, or various sliding contact points, or
alternatively, the loop sensor may be mounted inside
the spring or through the turns of the spring in
various ways such that its curvature is linearly
related to the linear movement of the pivot point.
This embodiment allows the use of a small curvature
sensor with limited travel to measure large
displacements.

It will be seen that the sensors described are
particularly convenient for being embedded in
structures. The loop sensors are particularly suited
for measurements in thin tubes, pipes, rods and the
like, particularly if measurements must be performed

50

near the ends of the member. The loop sensors are
well adapted for use in various probes that must be
inserted into small spaces. Applications for the
sensors in general are meant specifically to include
at least all applications that could potentially be
performed with strain gauges, plus others.

The sensor may be incorporated into a means of
trans- port, means for construction, agricultural
implement, robot, living body or a prosthetic device,
for detecting a movement relation to a further
movement or a point of reference.

Figure 37, which is similar to Figure 14,
illustrates one example of electronic circuitry that
can be used to measure the transmission of light
through a paired sensor element such as that shown in
earlier Figures. In Figure 37, fiber 39' (shown
coiled to indicate arbitrary placement and length of
the guide conveying light to and from the sensing
portion) has the light emitting strip at 30'. Fiber
45', which is otherwise the same as fiber 39', has no
sensing portion at position 46', which represents a
section of the fiber in close proximity to sensor
section 30'. Both fibers are illuminated by
photoemitters E1 and E2, which are light emitting
diodes. Photodetectors D1 and D2, which receive light
from the fibers, are PIN photodiodes, backbiased with
-12 Volts to enhance the speed of their response to
light energy. U1 and U2 are high input impedance
operational amplifiers arranged as transimpedance
amplifiers, converting light energy linearly into
voltages fed to the inputs of U3, which is an
operational amplifier connected as a differential
amplifier with a gain 10. The gain of amplifier U2
can be varied with R1 so that for a straight fiber,

51

the inputs to U3 are equal. In this condition, the
optoelectronic circuit is analogous to a two-armed
bridge such as is used to make strain-gauge
measurements. Errors due to degradations in the
fibers, connector variations, temperature
fluctuations, and the like tend to cancel before
reaching the output of U3. The output of U3 is a
voltage which varies with bending at the band portion
30'. The output voltage can be further amplified and
sent to a display unit or used to control various
parameters, such as actuators designed to minimize the
angle of bend.

Many variations of the circuitry are possible,
including variations with greater immunity to error
sources. One such variation would use the same light
source and detector, separating the signals by
chopping them at different frequencies and employing
synchronous detection. Another variation is to
replace U3 in the above Figures with a divider
circuit, so that the sensor signal is divided
arithmetically by the reference signal.

Another variation uses one photoemitter, for
example E1 in Figure 14, to illuminate the sensor
fiber, such as 19 in Figure 14, and also to illuminate
a reference fiber such as 25 in Figure 14. This last
variation may be further enhanced by eliminated U3,
using U2 and another amplifier to control the light
out of 25 to a constant value, and reading relative
light transmission through 19 directly from the output
of U2.

Figures 38, 39 and 40 illustrate other forms of
fiber sensors having normal circular cross-sections.

PHI 301656

In Figure 38 a sensor 70 is formed from a flat strip having a rectangular cross-section. It has two opposed wide flat surfaces or sides 71 and 72. The strip is bent into a U-shape, in the Example, in a plane parallel to the flat surfaces 71 and 72. A light emission surface 73 is formed on one of the flat surfaces, surface 71, at the curve 74, and in use a sensor deflects in a direction normal to the flat surface 71 as indicated by arrow F. This deflection or curvature is out of the plane of the fiber, and is illustrated in Figure 38B.

In Figure 39A, the sensor 70 is again formed from a flat strip having a rectangular cross-section, with opposed, spaced-apart, wide flat surfaces or sides 71 and 72. In this Example the strip is bent into a U-shape in a plane normal to the planes of the surfaces 71 and 72. Light emission surfaces 75,76 are formed on each of the surfaces 71 and 72, adjacent to the bend 77. The emission surfaces face in the same direction, as seen in Figure 39C particularly. The deflection is illustrated in Figure 39B.

Figure 40A illustrates a fiber sensor 80, with a D-shaped cross-section as seen in Figure 40B. In this Example, the fiber is bent in a U-shape, in a plane parallel to a flat surface 81 of the fiber, the bend indicated at 82. A light emission surface 83 is formed on the flat surface 81 at the bend 82. The deflection of the sensor would normally be downward out of the plane of the surface 81, as indicated at the dotted outline 80A.

Rectangular cross-sections, or similar cross-sections, have certain advantages. They can provide very efficient modulation of light by bending, as a

53

fiber having one predominant mode can be used.
Virtually all of the light can be made to intercept
the emission surface.

Figure 41 illustrates another sensor made of a
flat strip having a rectangular cross-section. It has
two opposed wide flat surfaces 71 and 72 and a light
emission surface or surfaces 84 and 85 on the same
surface, in this case surface 71. In this example the
strip is bent into a U-shape but in such a way that
the long axis of its cross-section is perpendicular at
section Q-Q' compared to the orientation of said long
axis at section R-R'. To maintain it in this shape
but with minimal effect on bending in a plane
perpendicular to the plane of the U-shape, a thin
rigid bar or bars 86 may be attached to the sensor
adjacent to where the orientation of the cross-section
begins to change.

Figure 41' is a graph of the light throughput of
a sensor like the one in Figure 41. In this case the
sensor was made of a strip of optically clear polymer,
with a cross-section of 0.18 mm x 1 mm and a total
length of 130 mm. The rigid bar had a cross-section
of 0.8 mm x 0.2 mm and was 3 mm long. It was placed
with its greatest width flat against the optical
strip, 4 mm from the apex of the loop. The structure
was held in a fixture, such that the loop was free to
flex out of the plane of the loop in a roughly
circular arc. The horizontal axis in the Figure
indicates curvature of the loop, expressed as a total
angular deflection from a planar (non-deflected) loop,
per 4 mm (the approximate length of the region of the
loop allowed to flex, measured along the axis of
symmetry of the loop). The vertical axis indicates
light transmission through the light guide expressed

54

as a percentage of the maximum transmission measured
during the test, where zero transmission corresponds
to no light travelling through the light guide. The
graph shows the ability to achieve a sensor with a
linear range which extends substantially into a region
of curvature such that increasing curvature produces
increasing light transmission.

Figure 42 shows a curvature or displacement
sensor 87 on fiber 89 affixed to a bending beam 88.
The bending beam is situated with one end 90 attached
to a reference structure 91. Arm 92 pivots relative
to the reference structure on hinge 93. Spring 94 is
attached under tension to the pivot arm by means of
pin attachments 95. This arrangement is used to
measure the pivot angle of arm 92 by means of
transmitting its angular displacement to the bending
beam 88, in such a way that extraneous movement of
pivot arm 92, such as end-to-end displacement,
minimally affects the curvature of said beam.
Alternatively, the spring may be replaced by a shear
pad or other structure that minimizes the number of
mechanical modes transmitted to said beam. This
method of attachment is useful in applications such as
automotive suspension height measurement and is
preferable to the use of a secondary bean at right
angles to primary beam, as in Y and T.

In the case of light guides with a cross-section
that is rectangular or otherwise non-circularly
symmetric, if the modes entering the loop (not
counting the mode-modulating effects of the surfaces)
are weighted toward being in the plane of the loop,
then it is best to apply bends to the assembly within
the plane of the loop. This is normally also the
plane of greatest flexibility for deflections. The

55

emission surfaces then logically must be perpendicular
to the plane of the loop, and must face such that all
undergo curvatures of the same sign. In this case
this is the optimum configuration because the
predominant modes are those affected by the
modulation, regardless of loop geometry. In the case
of non-circularly symmetric light guides where one
mode substantially outweighs all others, there is
little chance of mode-mixing downstream of the
emission surface or surfaces, so that the surfaces
need not be placed on or near the loop to achieve
optimum modulation. An example of such a sensor light
guide would be a thin strip of clear optical polymer
with a rectangular cross-section, such that the major
axis of the cross-section is perpendicular to the
plane of the loop. If the loop is in the plane of the
paper, apex facing right, then all the emission
surfaces would be placed on sides of the light guide
which face, e.g., the top (alternatively all face the
bottom) of the paper.

The response of sensors is explained in the
following way:
    Light rays travel along fiber optics throughout
    a range of angles limited by the difference in
    index of refraction between the core and the
    cladding. For straight fibers, some light rays
    pass through the emission band. As a fiber with
    the emission band at the top bends downward, more
    of the rays impinge on the band at angles capable
    of passing through the surface, either by
    diffusion or by direct transmission. As the
    fiber bends upward, fewer rays will impinge on
    the band, and will be at shallow angles to its
    surface, so that more of them stay within the
    fiber,   refracting   from   the   untreated

core/cladding boundary toward the fiber outside the sensor region. Bends at right angles to the axis of maximum sensitivity change to a minimum degree the amount of light striking the emission band, so there is virtually no change in transmitted light.

The width of the emission band around the circumference of the fiber will determine the sensitivity of the fiber to bends, with wider bands producing a larger percentage change per degree of bend. However, very wide bands will tend to increase the sensitivity to bends in the axis of minimum sensitivity. Typical sensors have emission bands that cover 5˚ to 30˚ of the circumference of the fiber, but other values will work. The length of the emission band can vary. It can be any length from millimetres to meters but there is less gain in sensitivity for long lengths, than expected. There is an optimum length for the strip, which is a function of the diameter of the fiber, its emission band width, and the mini- mum linear deflection angle desired. For 1 mm fibers, the optimum is about 25-50 mm, and for 200 micron fibers, it is about 10-20 mm. Long sensors can be formed by alternating lengths of fibers with an emission strip with lengths of fully clad fibers. Short sensors will be less sensitive, but more specific as to location of bend along the length of the member to which they are attached. However very short sensors can be made, such as 8 mm sensors on 125 micron fibers.

Sensors in accordance with the invention have various advantages, and useful characteristics. No special electronics are required to measure interference patterns, it is only necessary to measure the amount of light transmitted. Cost is orders of

57

magnitude below that for interference (OTDR)
techniques. Sensitivity is in the same range as that
of resistance strain gauges. For many situations,
particularly when the sensors are mounted near the
neutral axis of a bending beam, changes in signal per
microstrain are greater than those for resistance
strain gauges, as measured in percent. The linear
range is very large. They are particu- larly suited
to measurement of bending in aircraft wings,
helicopter blades, machinery, robot arms, or large
structures. They are not affected by temperature,
since measurement is not dependent on small changes in
length of the fiber or its sensing portion. This is
a distinct advantage over resistance strain gauges,
which have a relatively narrow range of tem- perature
sensitivity unless compensated, and over interference
techniques, which are affected even more by
temperatures than are resistance gauges. They can be
used to measure position, with a large dynamic range.

While the above are descriptions of various
prefer- red embodiments of the invention, various
modifications should be obvious to those skilled in
the art. For example, the sensor may be used with
virtually any wavelengths or light including broadband
or discrete spectra. Various referencing methods may
be used, including a separate untreated fiber that is
used to send light from the sensor light source over
a similar path as the sensor fiber, the intensity of
said light being used to perform differential or ratio
compensation for common mode errors such as variations
in fiber transmission or light source intensity. The
reference path may also be used to automatically
adjust the source light intensity to a fixed level.
The invention is also meant to allow for emis- sion
surfaces that allow light loss at one wavelength or

58

band of wavelengths but not at another wavelength or
band of wave- lengths.   Thus, a two wavelength
referencing method could be used over the same fiber,
wherein light loss due to curvature is sensed with one
wavelength and the other is used to provide reference
information for compensation for common mode errors.
Also, the light path may be chopped or modulated to
provide improved sensitivity, if necessary.   The
output of the sensor may be used to measure parameters
over a large range, or to determine a switching level.
The sensors may be used for measurement, or form a
part of a control loop.   The sensor fiber may be
attached to a substrate that is undergoing bending, or
the fiber alone, supported by two or more parts whose
deflection is being measured, may be the element being
bent.   Consequently, the description should not be
used to limit the scope of the invention.

59

I CLAIM:

1.   A fiber optic bending and position sensor comprising a fiber optic light guide having at least one light emission surface extending, for part of the length of the guide, in a direction selected from:

a substantially peripheral direction, and

a substantially curved axial direction when in a curved portion of a curved guide.

2.   A sensor as claimed in Claim 1, having the light emission surface in the form of a plurality of closely spaced peripherally-oriented bands.

3.   A sensor as claimed in Claim 1, having the light emission surface in the form of a ring around the periphery.

4.   A sensor as claimed in Claim 1, wherein the light emission surface or surfaces are positioned so as to give the most desirable orientation to the maximum sensitivity plane.

5.   A sensor as claimed in Claim 1, including means for injecting a light beam into one end of said light guide and means for detecting said light beam at the other end of said light guide.

6.   A sensor as claimed in Claim 5, including means for measuring the difference in intensity of said light beam between said one end and said other end of said light guide.

7.   A sensor as claimed in Claim 6, including display means for indicating any said difference in

60

intensity of said light beam as a bending or
displacement of said light guide.

8.   A sensor as claimed in Claim 1, including a
further fiber optic light guide positioned alongside
said fiber optic light guide, said further light guide
having an unbroken cladding layer and forming a
reference light
guide.

9.   A sensor as claimed in Claim 1, having said
light emission surface or surfaces covered by a light
absorbent material.

10.   A sensor as claimed in Claim 1, comprising
a fiber optic light guide in the form of a loop, the
loop having the light emission surface therein.

11.   A sensor as claimed in Claim 10, wherein the
loop has a plurality of light emission surface regions
therein.

12.   A sensor as claimed in Claim 11, wherein the
surface regions in the curved loop are in a
configuration selected from
    (a)   peripherally-oriented bands grouped on an
inside or concave portion of the curvature of the
loop;
    (b)   axially-oriented bands substantially in the
plane of the loop and following the curvature of the
loop.

13.   A sensor as claimed in Claim 12 (a) having
three to five peripherally-oriented bands grouped
together, with the bands each extending for about 60°
to about 90° of periphery.

61

14. A sensor as claimed in Claim 12 (b) having from two to six curved bands either coplanar or in parallel planes.

15. A sensor as claimed in Claim 10, wherein light emission surface or surfaces are positioned so as to give the most desirable orientation to the maximum sensitivity plane.

16. A sensor according to Claim 1, wherein the sensor is a suspension sensor comprising a flexible beam and said fiber optic curvature and displacement sensor mounted to said flexible beam, said sensor comprising a fiber optic light guide having at least one light emission surface extending, for part of the length of the guide, in a direction selected from:
        a substantially peripheral direction, and
        a substantially curved axial direction when in a curved portion of a curved guide.

17. A sensor as claimed in claim 1, comprising a fiber optic light guide having a rectangular cross-section, said light emission surface on at least one side of said cross-section.

18. A sensor as claimed in claim 17, said rectangular cross-section being oblong and including two spaced parallel wide sides, said light emission surfaces on one of said wide sides.

19. A sensor as claimed in claim 18, said light guide being bent into a V-shape on a plane parallel to planes of said wide sides, said bend forming said curved portion.

20. A sensor as claimed in claim 18, said light guide bent into a U-shape in a plane normal to said planes of said wide sides, said bend forming said curved portion.

21. A sensor as claimed in claim 20, a light emission surface on each of said wide sides, adjacent said bend.

22. A sensor as claimed in claim 1, comprising a fiber optic light guide having a D-shaped cross-section, having a flat surface on one side, said light emission surface formed on said flat side.

23. In a vehicle suspension system which includes an electronic system for sensing displacement between a vehicle body or frame and a vehicle wheel system, wherein the improvement comprises a suspension sensor comprising a flexible beam and a fiber optic curvature and displacement sensor mounted to said flexible beam, said sensor comprising a fiber optic light guide having at least one light emission surface extending, for part of the length of the guide, in a direction selected from:

a substantially peripheral direction, and

a substantially curved axial direction when in a curved portion of a curved guide.

24. A sensor according to claim 1, incorporated into a means of transport, means for construction, agricultural implement, robot, living body, sports equipment or a prosthetic device for detecting a movement relative to a further movement or a point of reference.

63

25. A method of sensing curvature and displacement, of an elongate member, comprising attaching a fiber optic light guide to said member, said light guide having a light emission surface extending, for part of the length of the guide, in a direction selected from:

a substantially peripheral direction, and

a substantially curved axial direction when in a curved portion of a curved guide, said light guide extending along said member; injecting a light beam into one end of said light guide, detecting said light beam at the other end of said light guide, measuring the difference in intensity of said light beam between said one end and said other end, indicating bending, or displacement, of said member.

26. The method of claim 25, including attaching a plurality of fiber optic light guides to said elongate member, each having a plurality of light emission surfaces such that the planes of maximum sensitivity of the guides are at different angles from each other so that at least one guide maximally indicates curvature at a unique planar inclination.

27. The method as claimed in Claim 26, utilizing two to six fiber optic light guides, said surfaces oriented in different directions at predetermined angles relative to each other.

28. The method as claimed in Claim 25, including attaching a further fiber optic light guide alongside said fiber option light guide, said further fiber optic light guide acting as a reference light guide.

29. The method of claim 25 which includes selecting the light guide so as to optimize sensing of

64

curvatures over a range that includes, as a substantial portion of the total substantially linear range sensed, curvatures that produce increasing transmission of light with increasing curvature.

30. The method of claim 25 which includes the use of shear elements or springs to communicate displacement to the elongate member, such that curvature of said member maximally represents the mode of displacement to be measured.

31. The sensor of claim 1 in which the fiber optic light guide, or portion thereof, is in the form of a single fiber which, serves both to illuminate the light emission surface or surface, and to collect illumination which has passed said light emission surface or surfaces, the illumination end and collection end of the fiber being located in a single region removed from the light emission surface or surfaces.

32. The sensor of claim 31 wherein the single fiber forms a narrow loop, at least a portion of the light emission surface is in the loop, and the apex of the loop is at the distal extremity removed from the illumination and collection region.

FIG. 1

FIG. 2

FIG. 3

FIG.4

FIG.5

SECTION X-X

FIG.6

FIG.7

FIG.8

SECTION Y-Y

FIG.9

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FIG. 10

FIG. 11

FIG. 12

SECTION Z–Z

FIG. 13
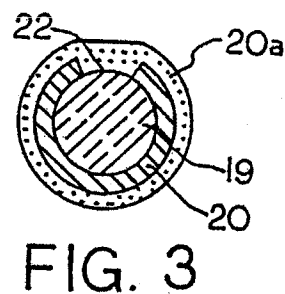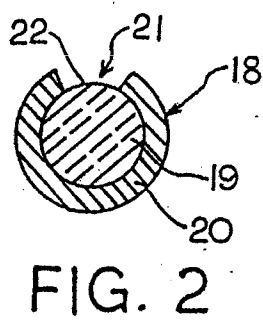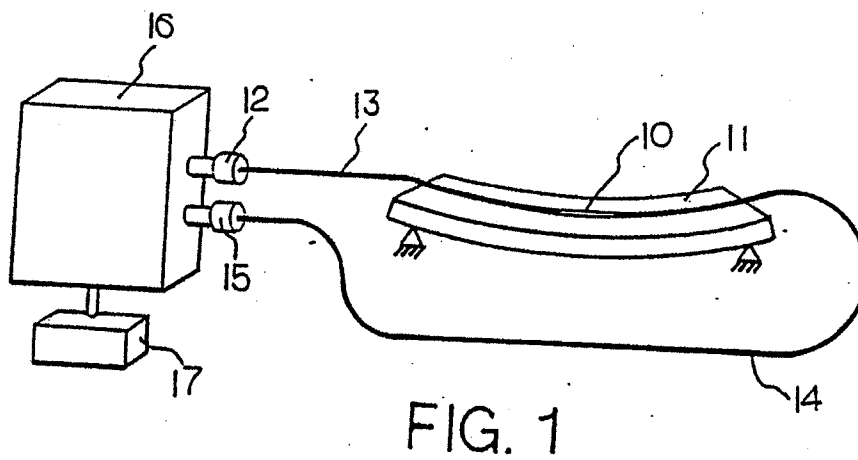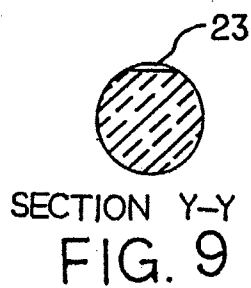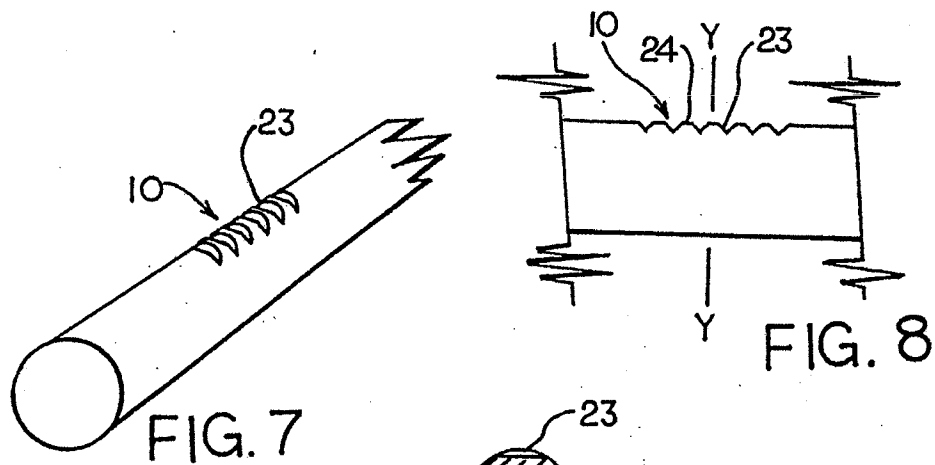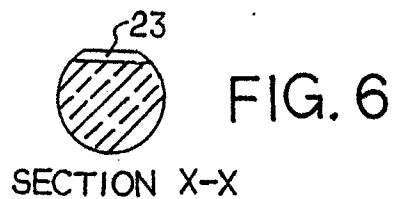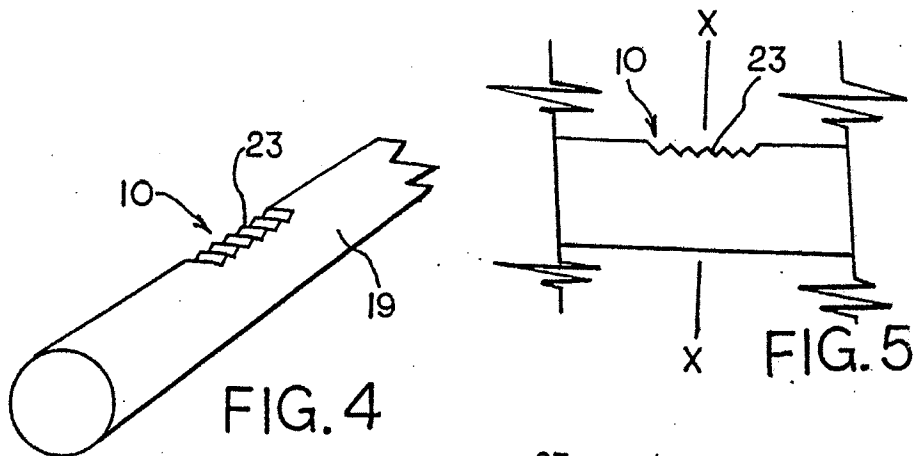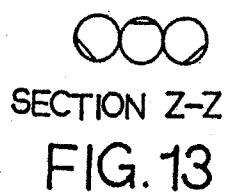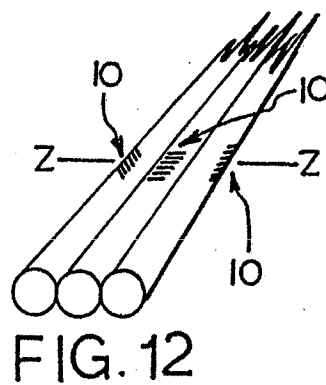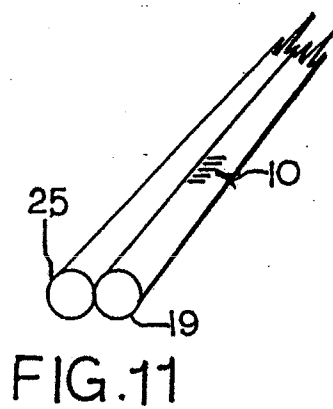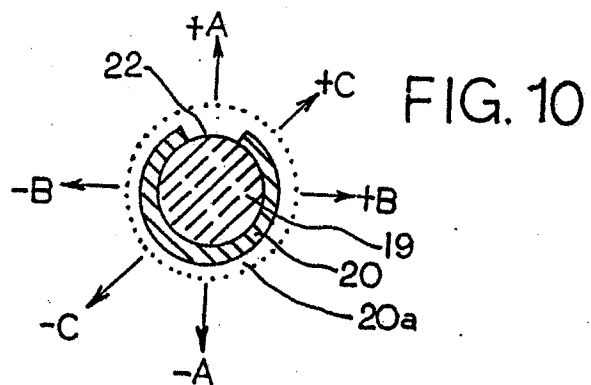
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FIG. 14

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FIG. 15

FIG. 16

FIG. 17

■ MAX AXIS
□ MIN AXIS

BEND DEGREES

INCREASE % RE STRAIGHT FIBER
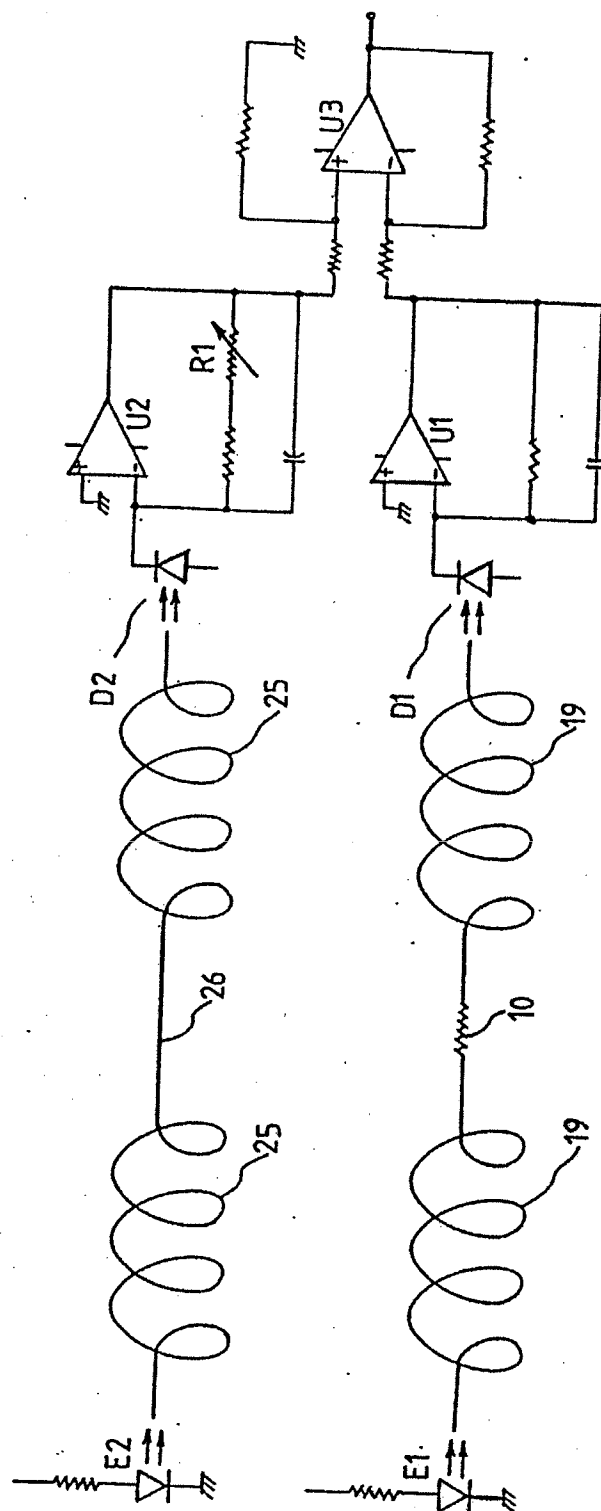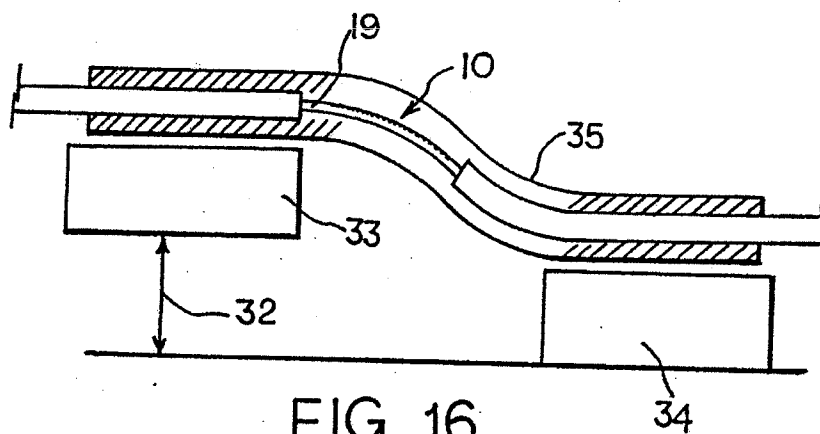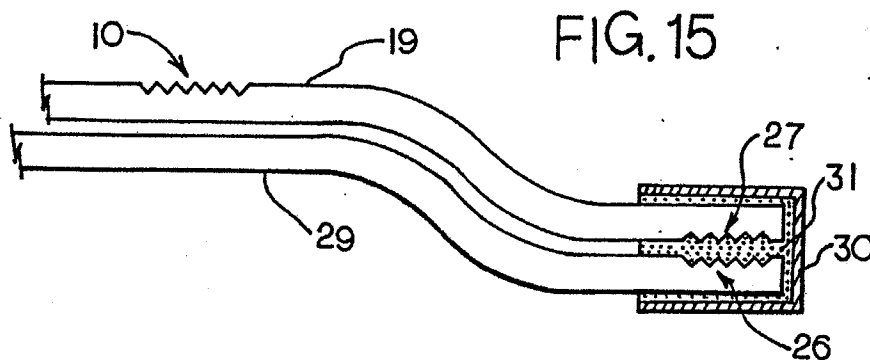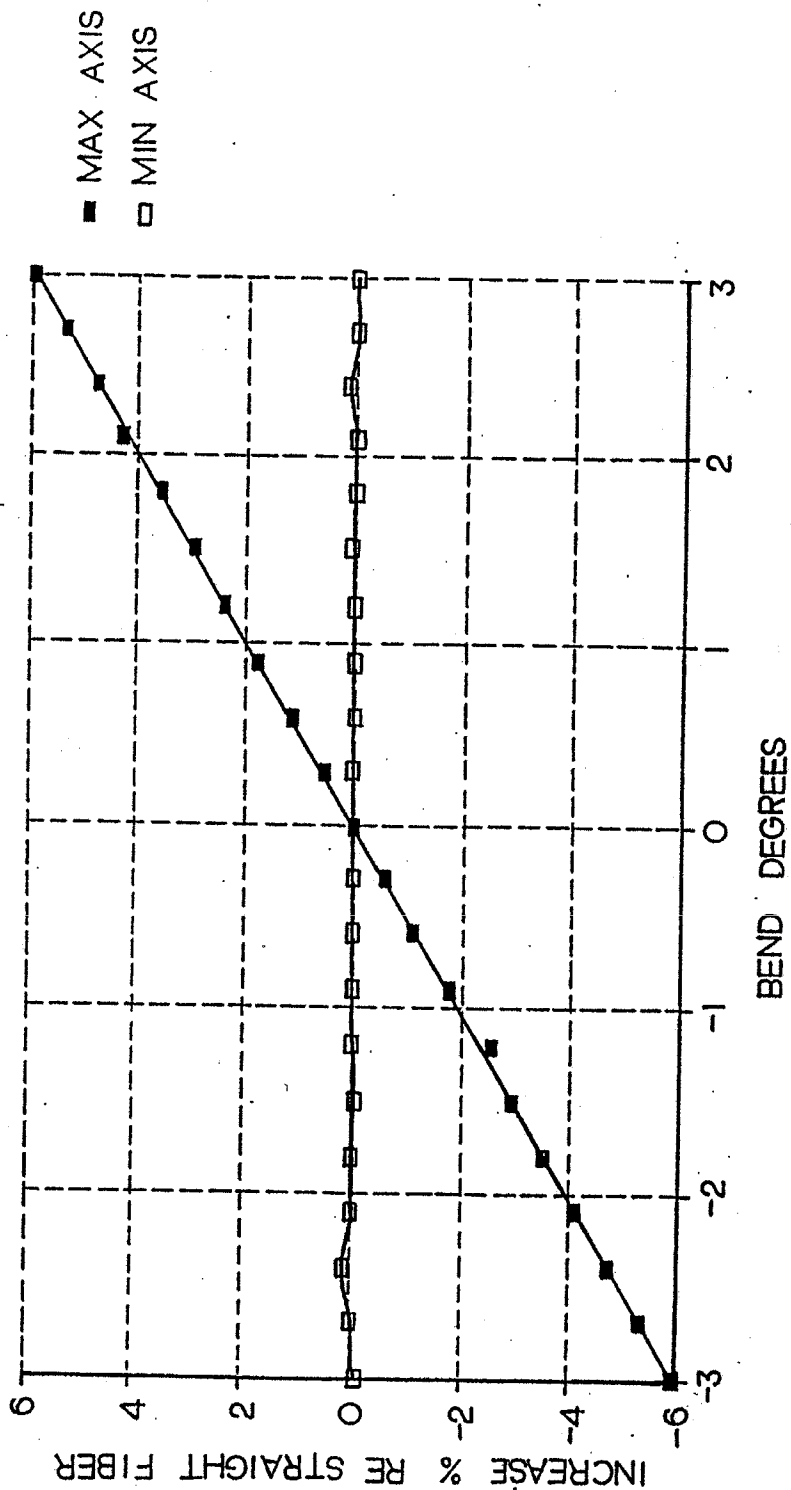
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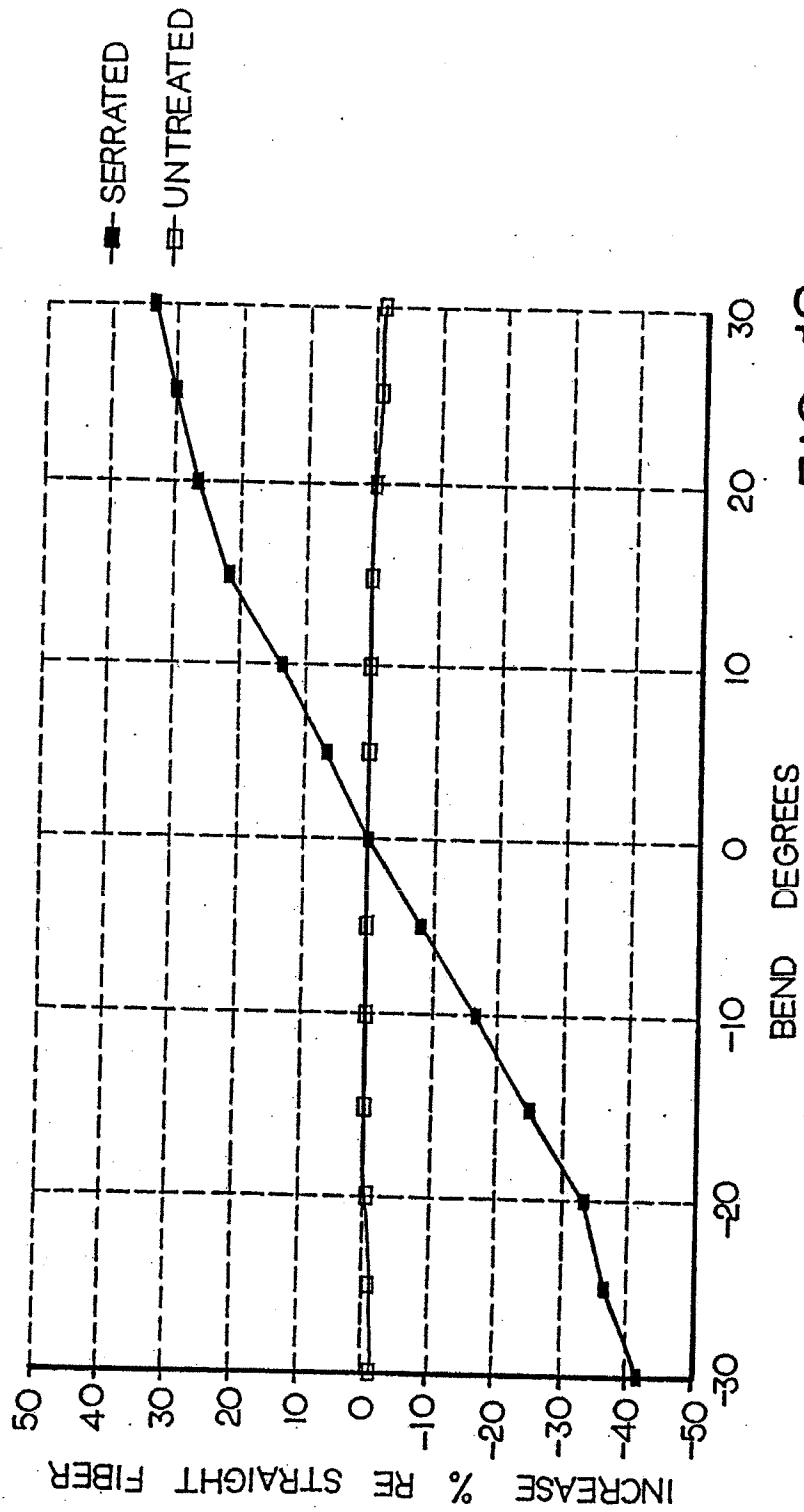
FIG. 18

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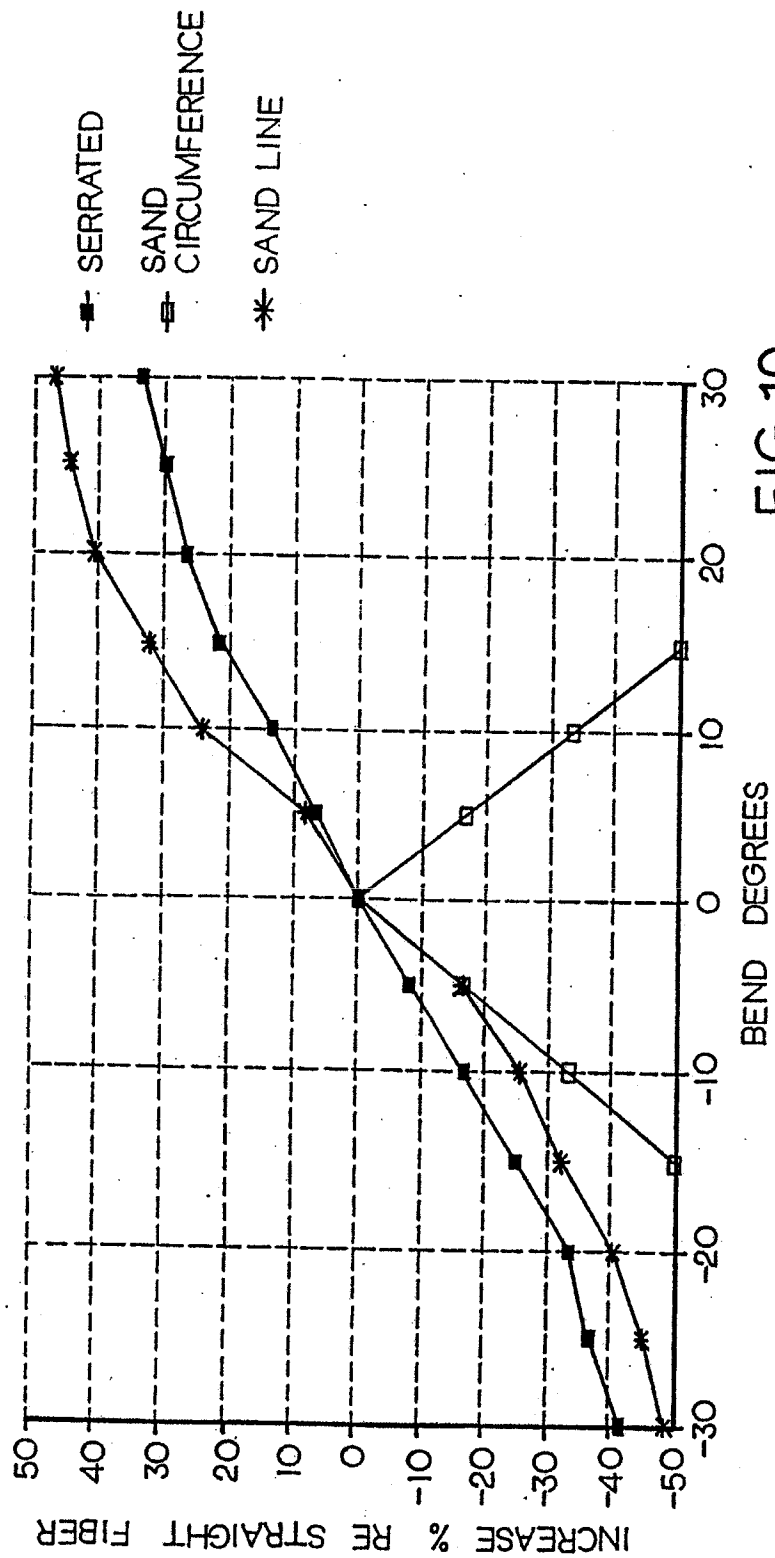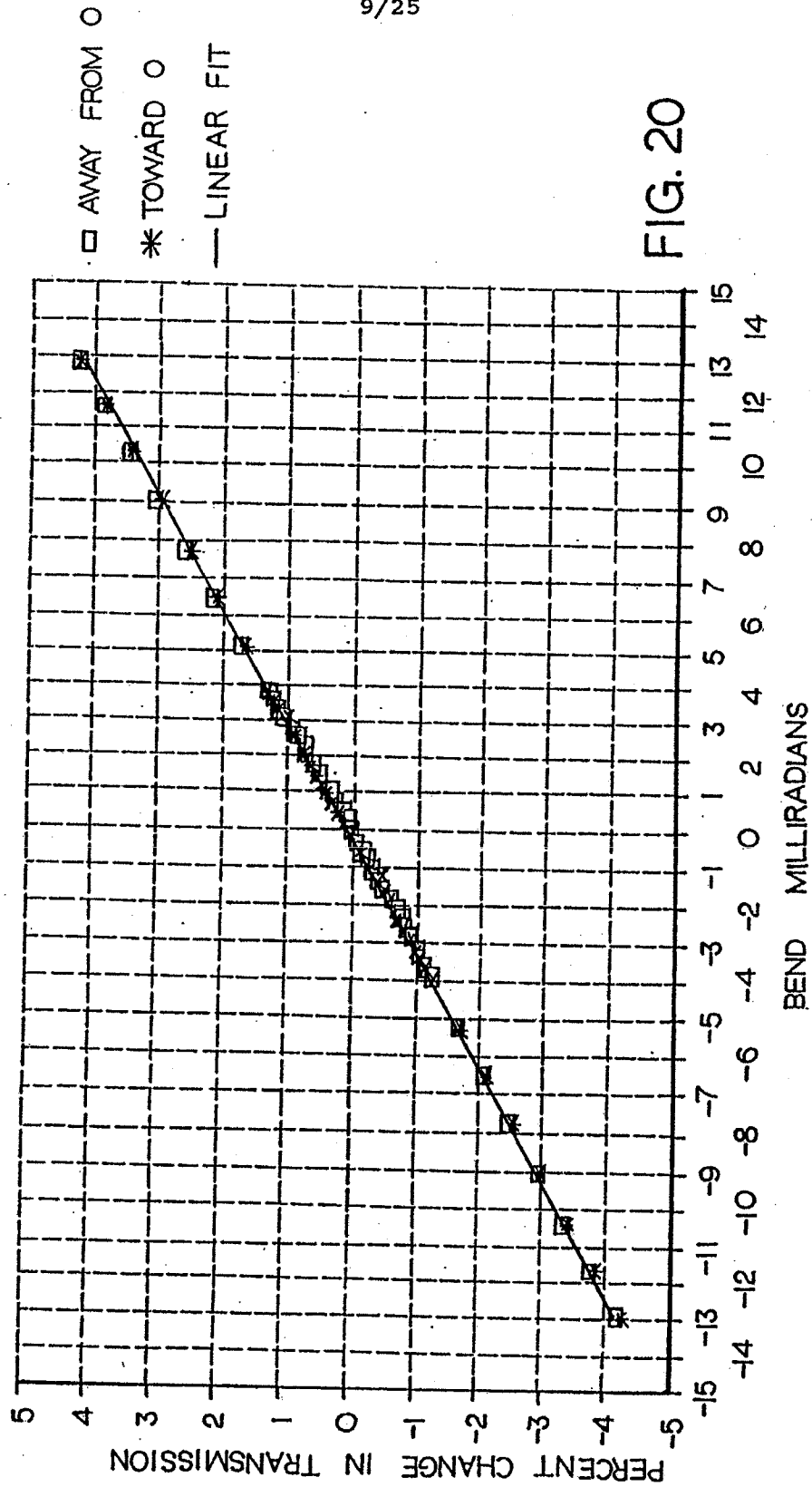
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FIG.19

FIG. 20

FIG.21

FIG. 22A

FIG. 22B

X—X

FIG. 22C

Y—Y

FIG. 23A

FIG. 23B

Z—Z

FIG. 23C

P—P
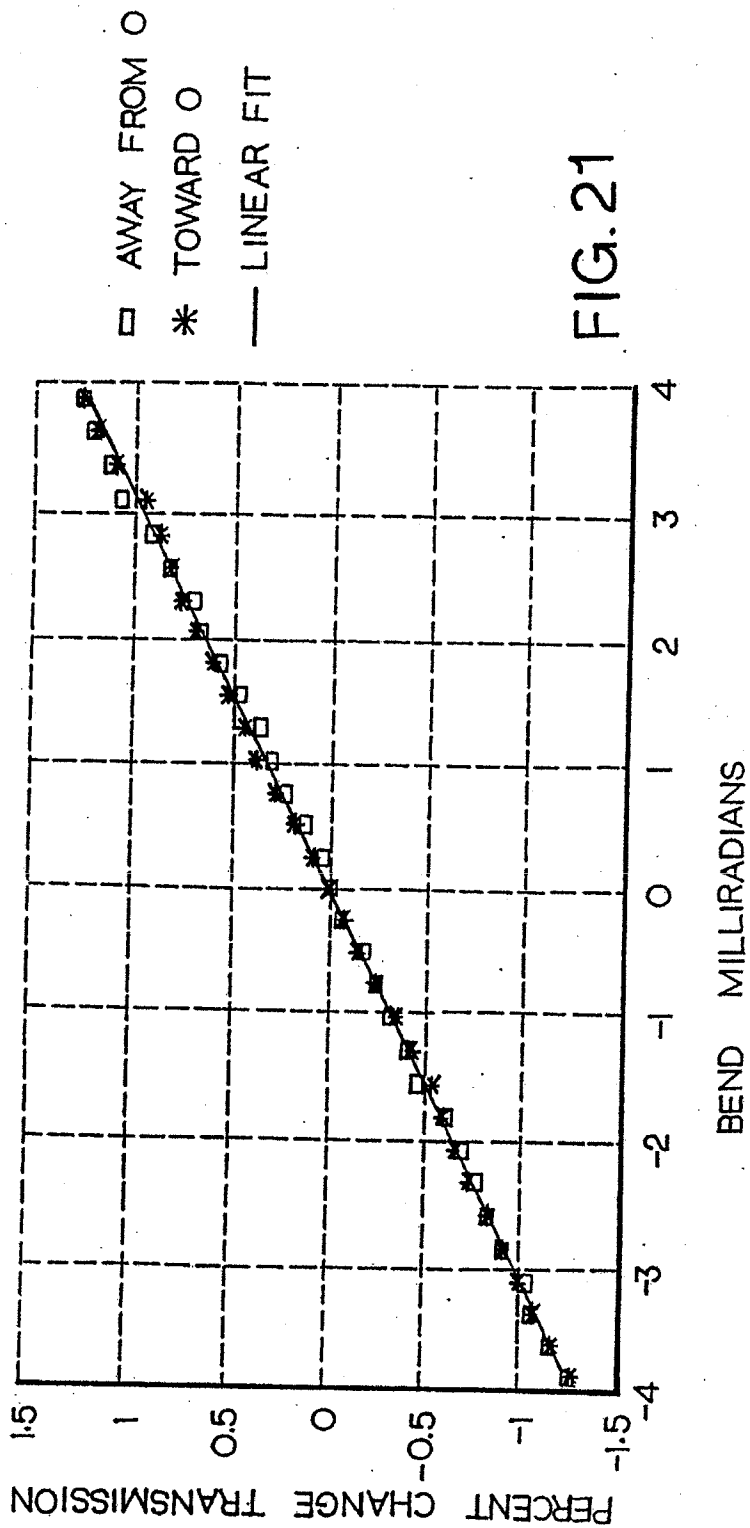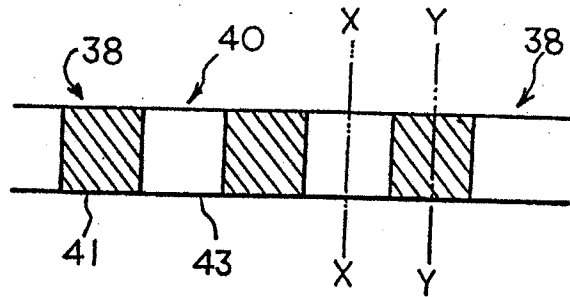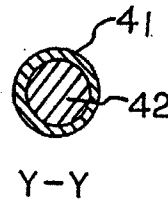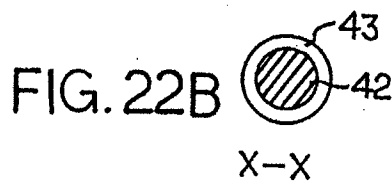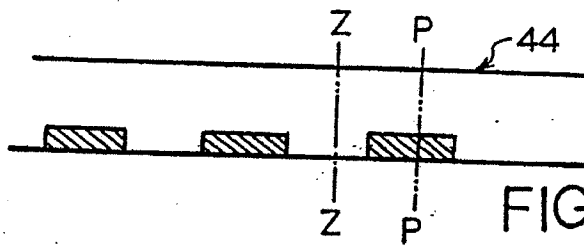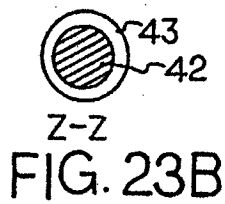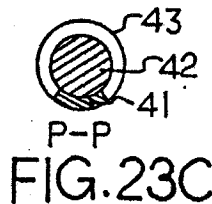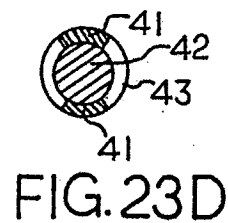
FIG. 23D

SUBSTITUTE SHEET
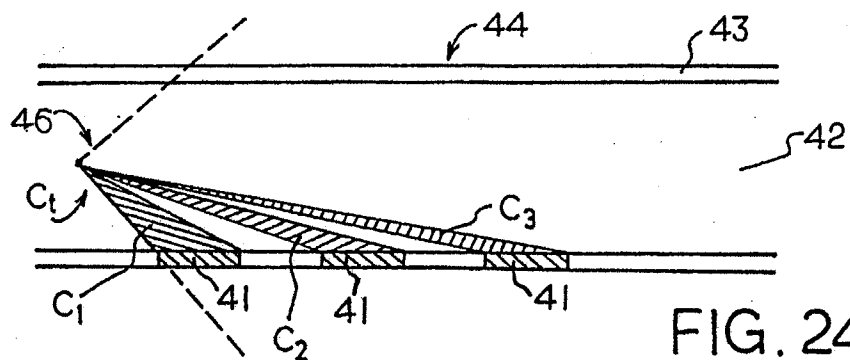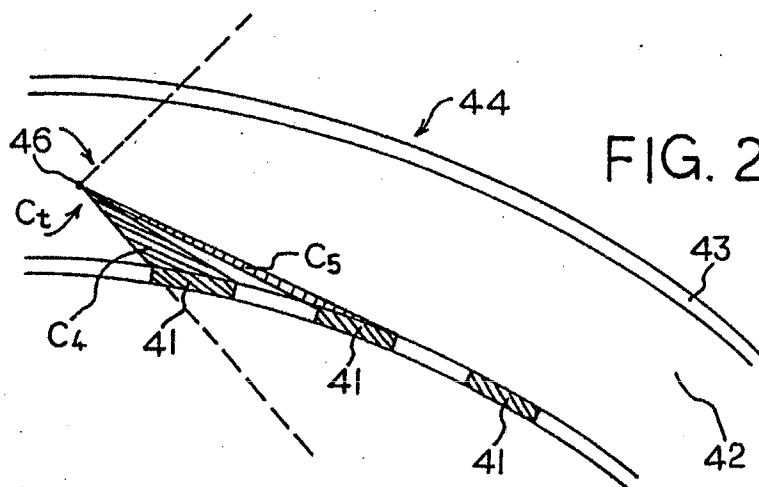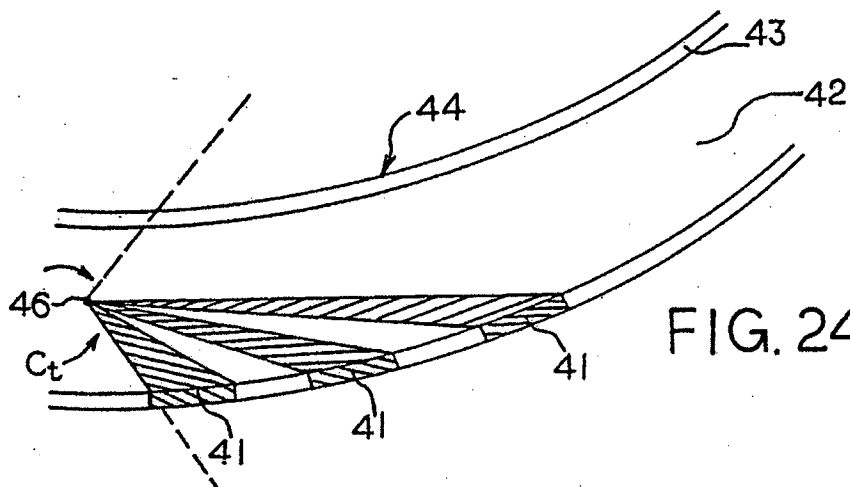
FIG. 24A

FIG. 24B

FIG. 24C

SUBSTITUTE SHEET
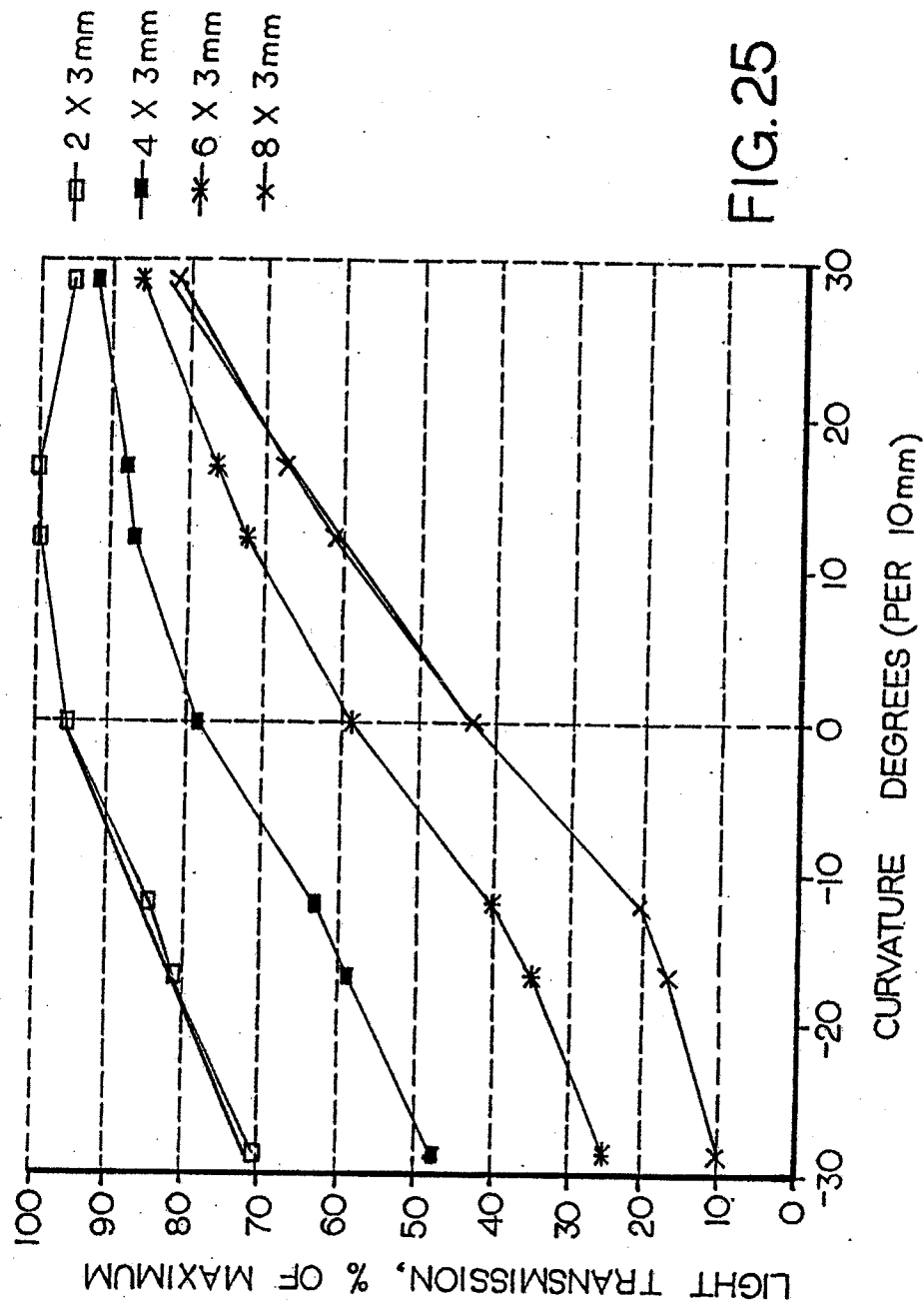
FIG. 25
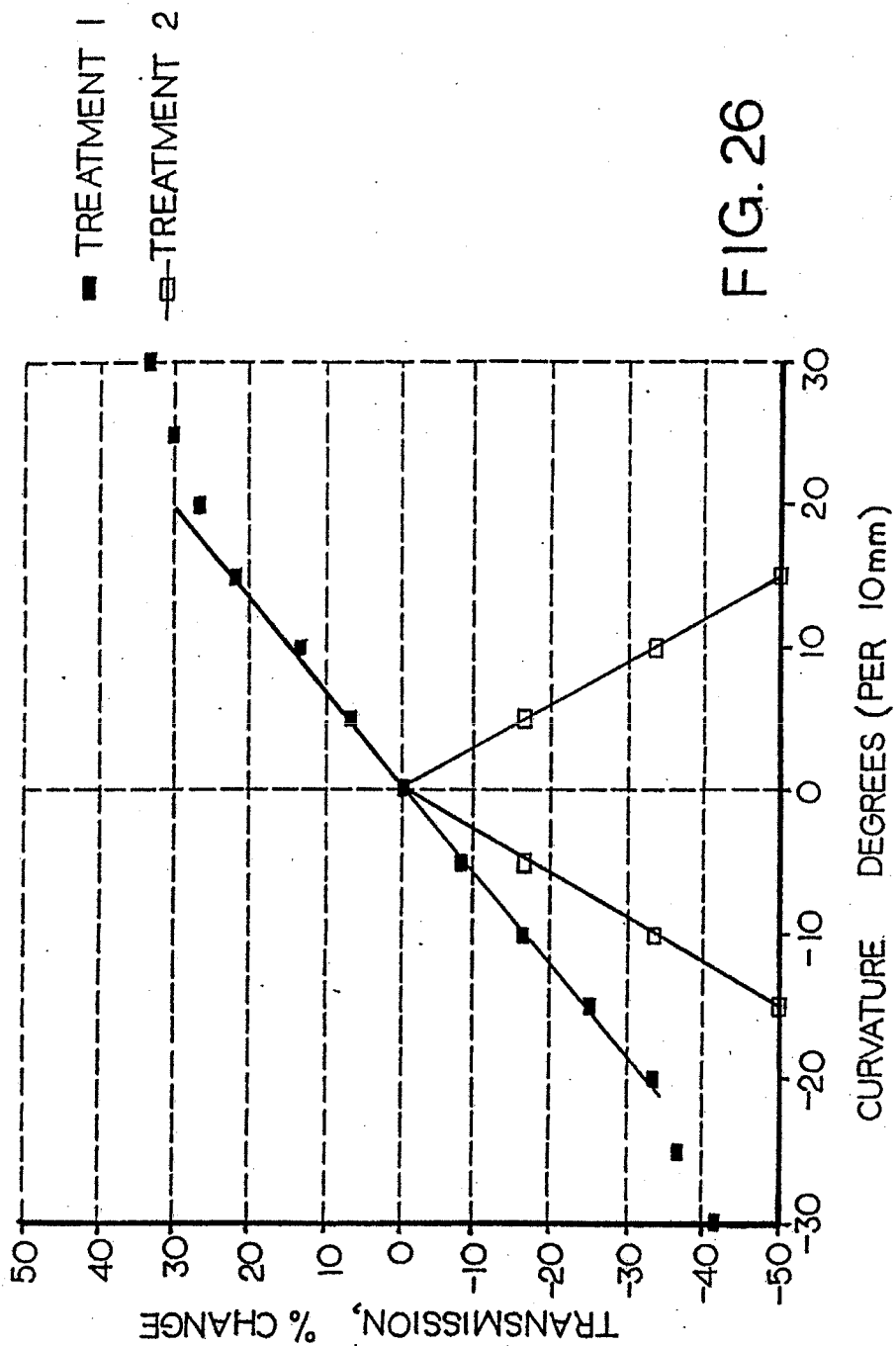
FIG. 26

FIG. 27
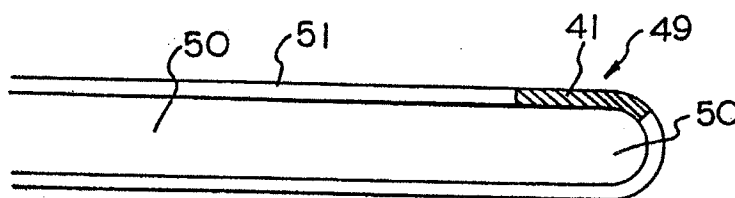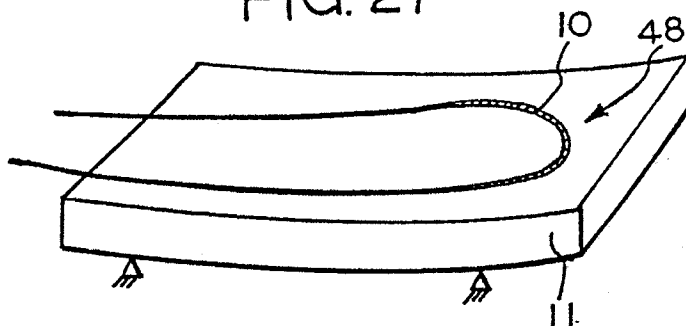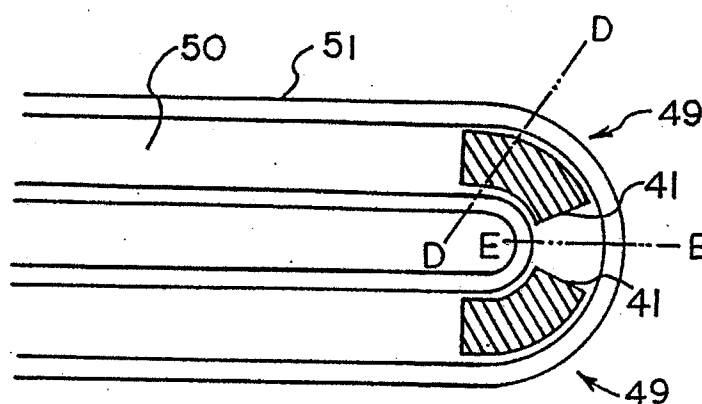
FIG. 28A

FIG. 28B

SUBSTITUTE SHEET
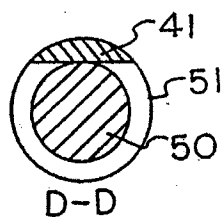
FIG. 28C
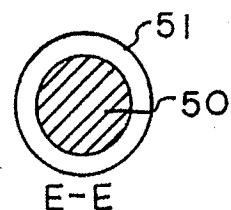
FIG. 28D

FIG. 28E

FIG. 28F

FIG. 28G

SUBSTITUTE SHEET

FIG. 29A

FIG. 29B

A−A

FIG. 29C

B−B

FIG. 30A

PHI 301686

A-A
FIG.30B

B-B
FIG.30C

C-C
FIG.30D

FIG. 31A

FIG.31B
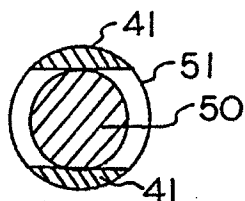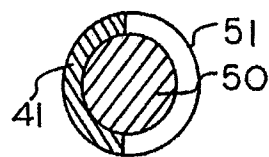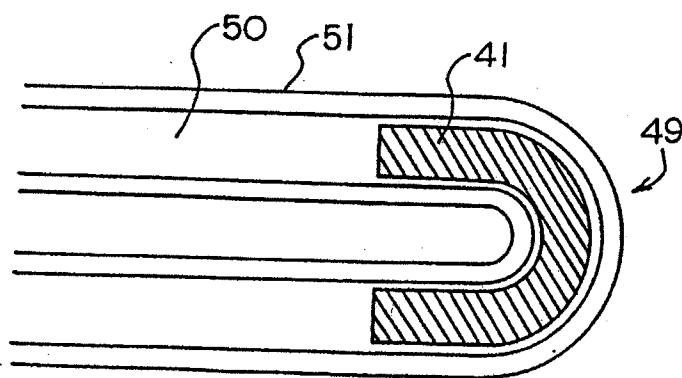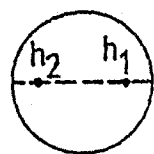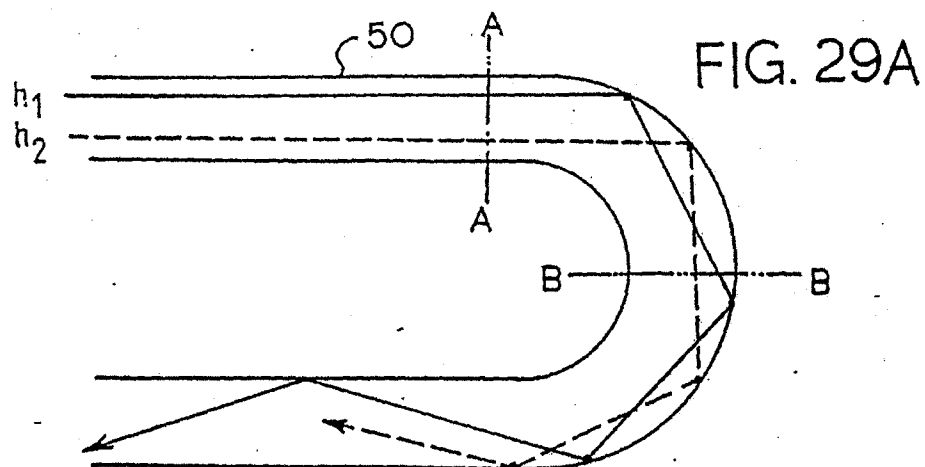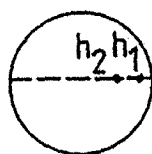
FIG.32A
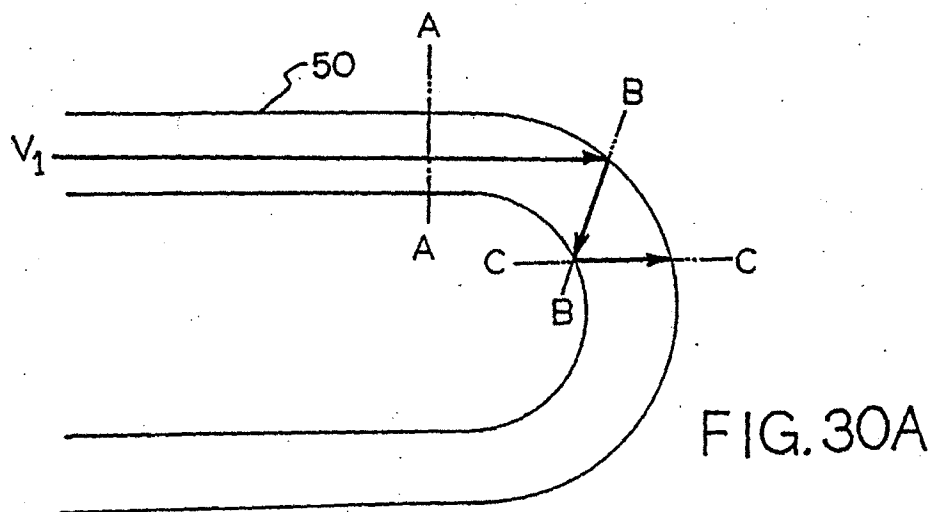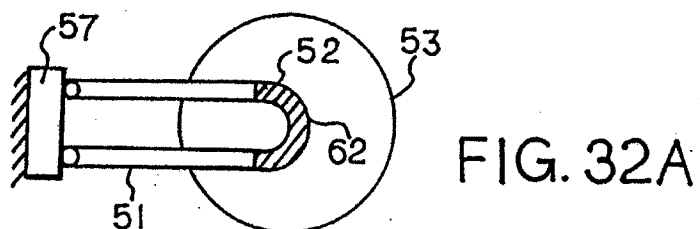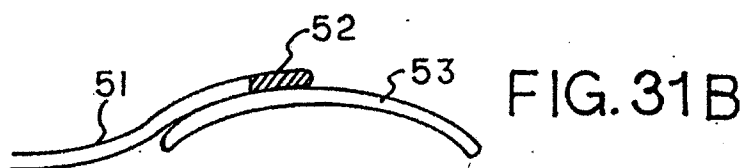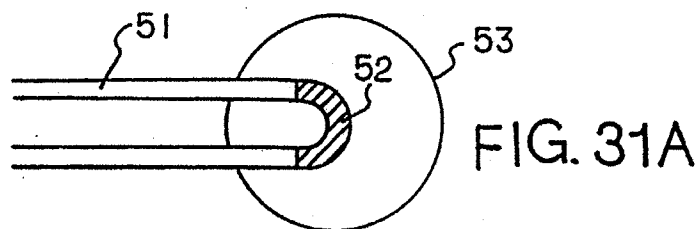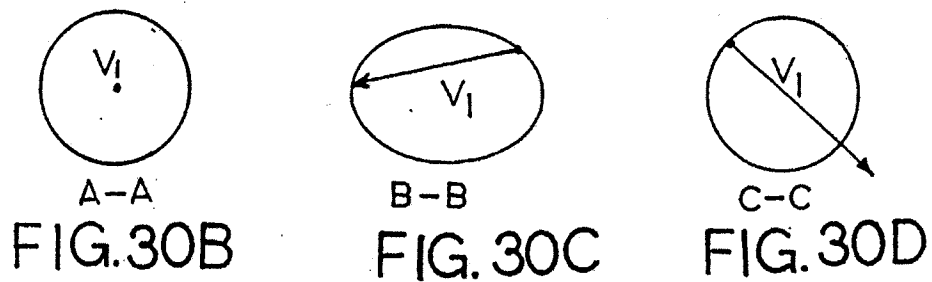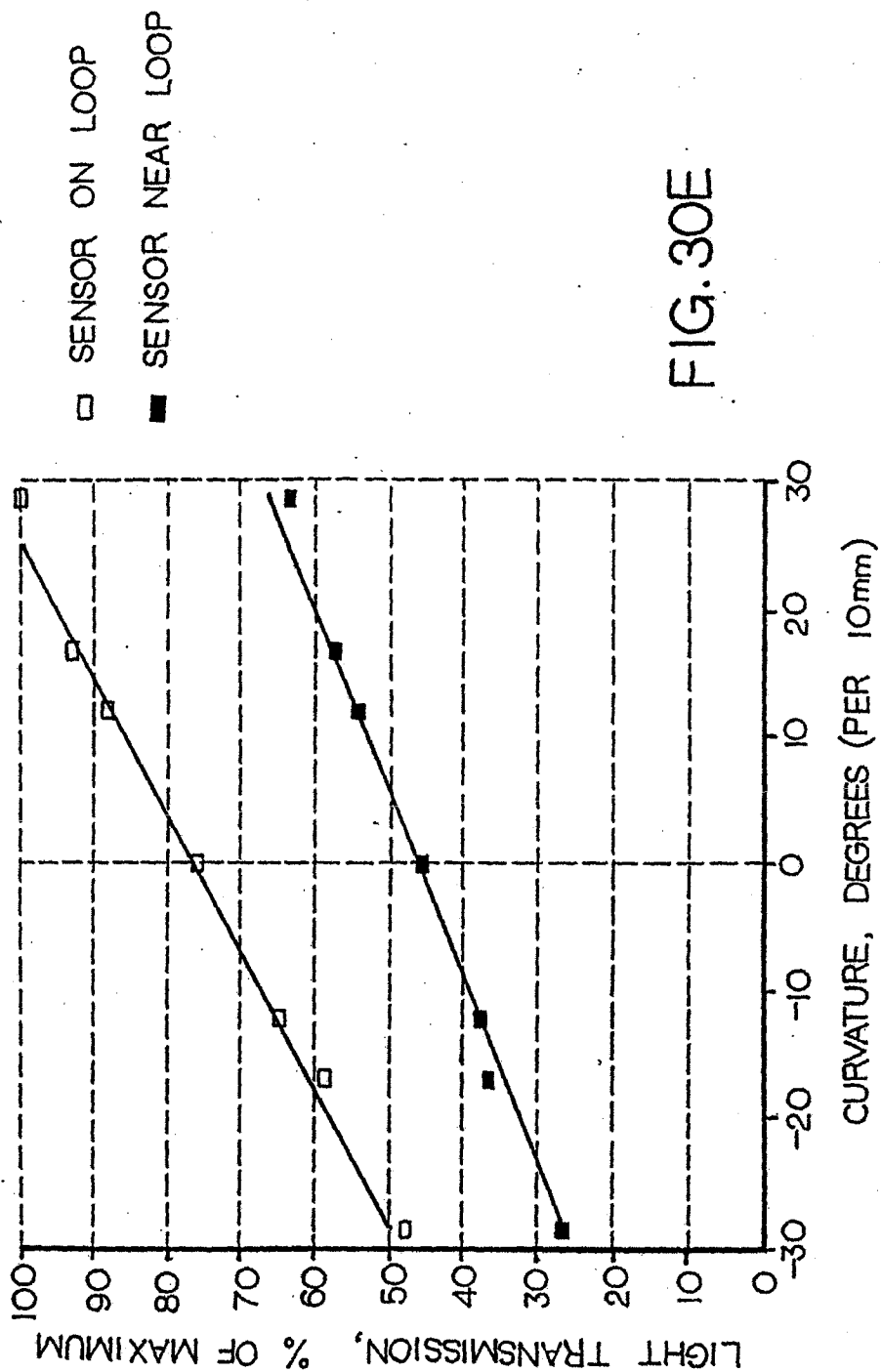
SUBSTITUTE SHEET

FIG.30E
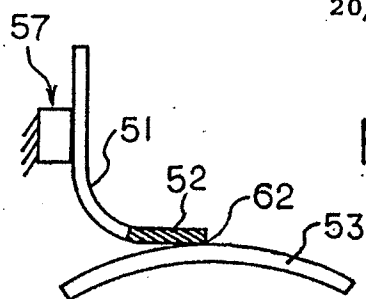
FIG.32B
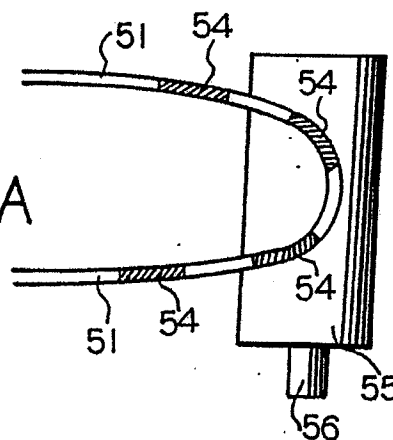
FIG.33A

FIG. 33B

FIG. 34
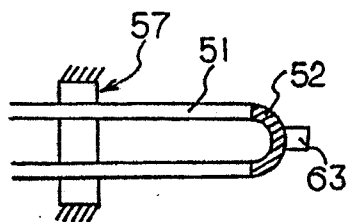
FIG.35A

FIG.35B

FIG.36

PHI 301690

FIG. 37

PHI 301691

FIG.38A

FIG.38B

FIG.39A

FIG.39B

FIG.39C
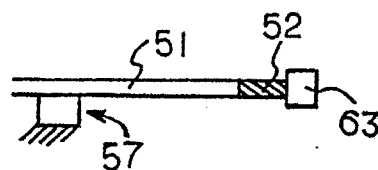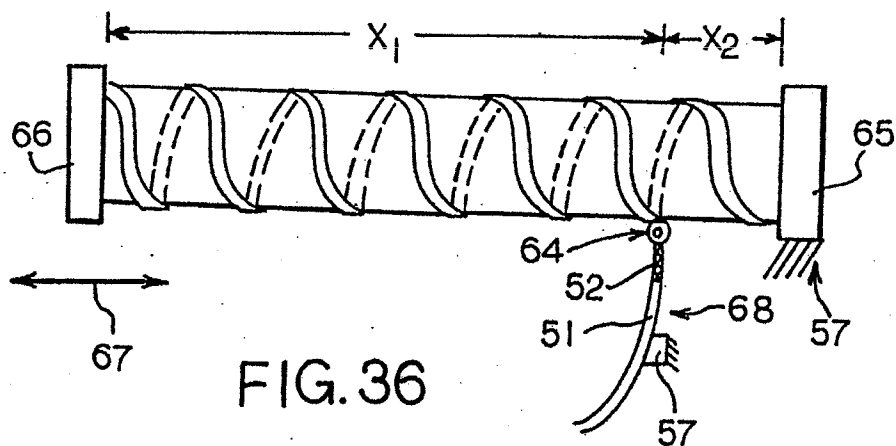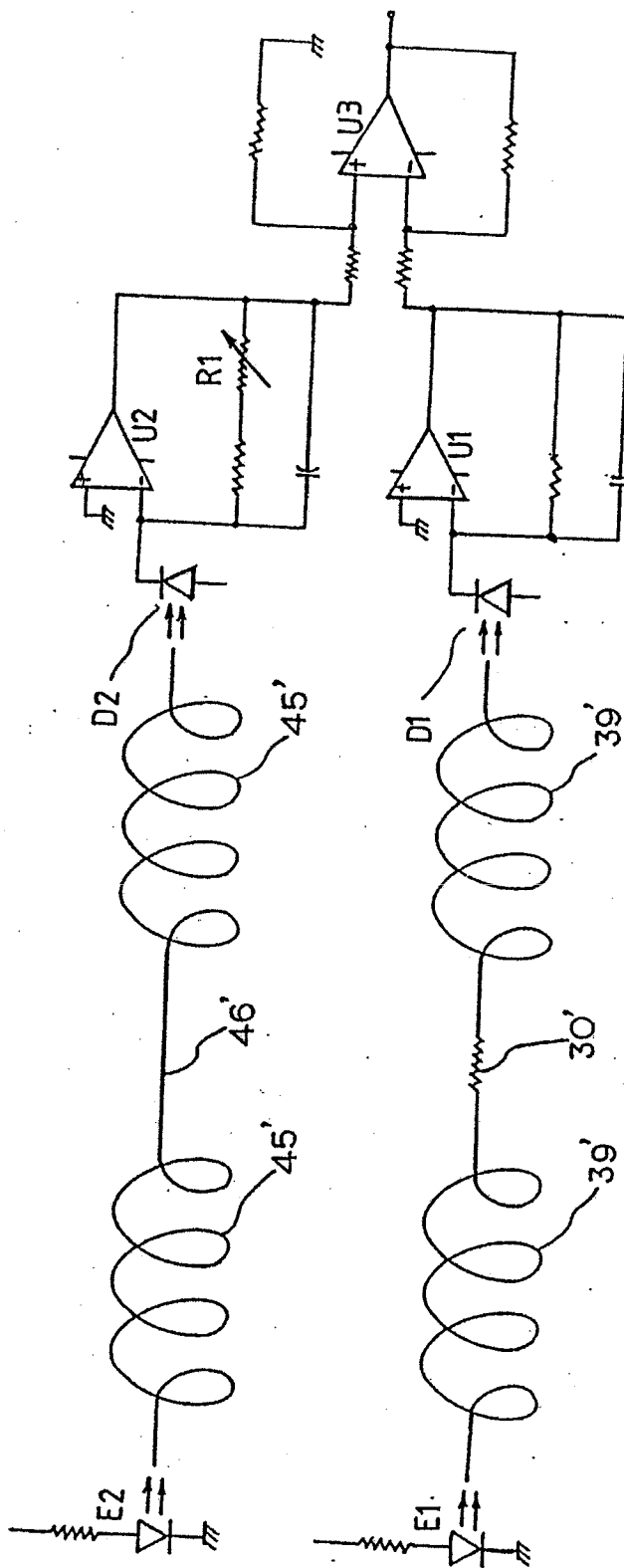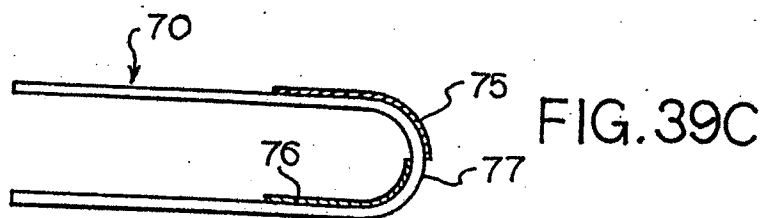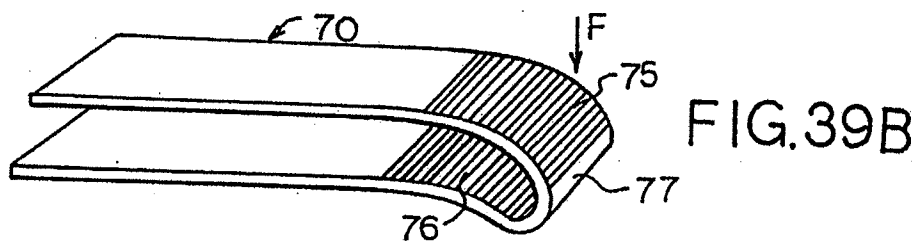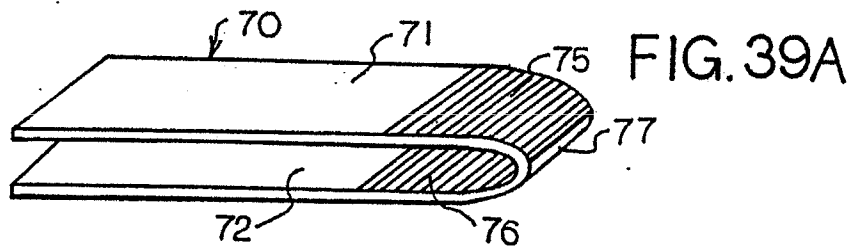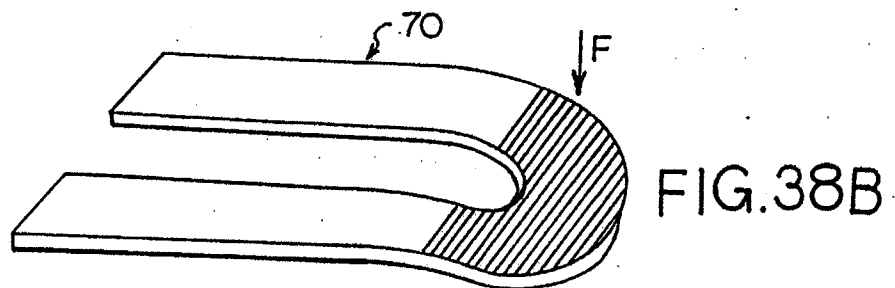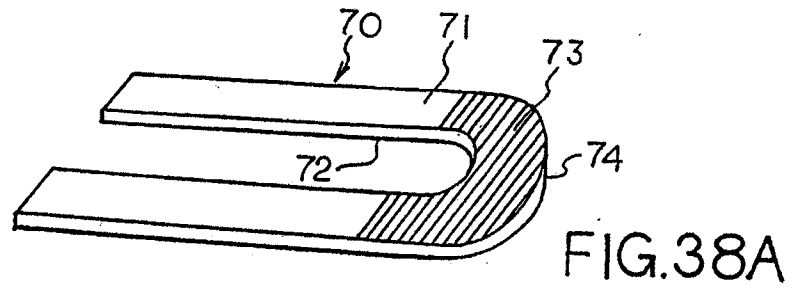
SUBSTITUTE SHEET

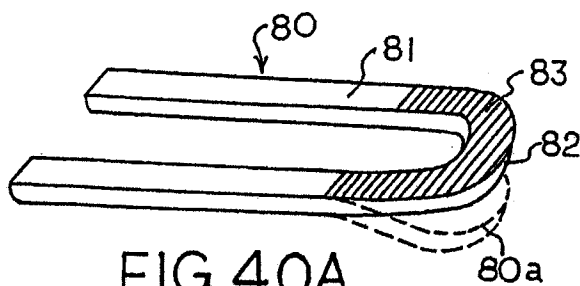FIG.40A
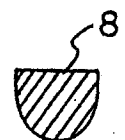
FIG.40B
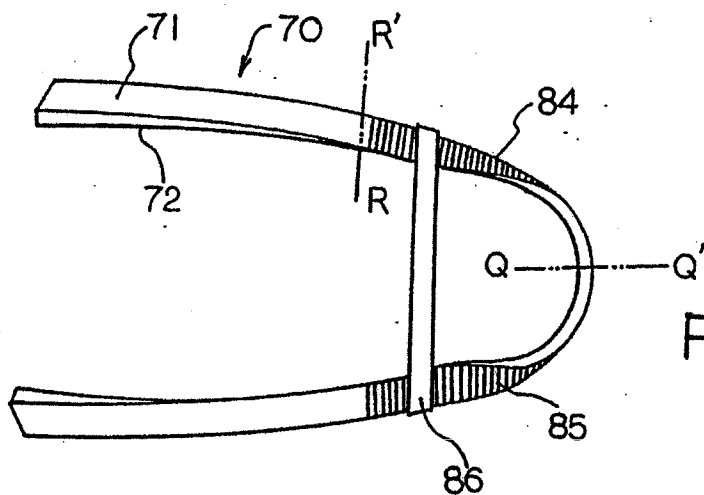
FIG.41
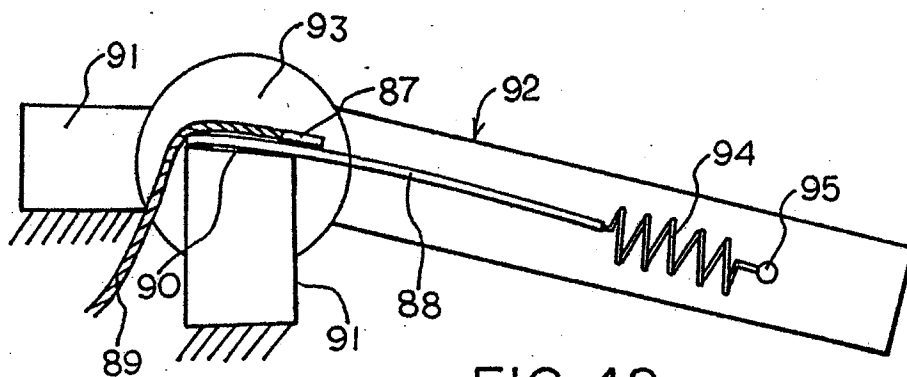
FIG.42
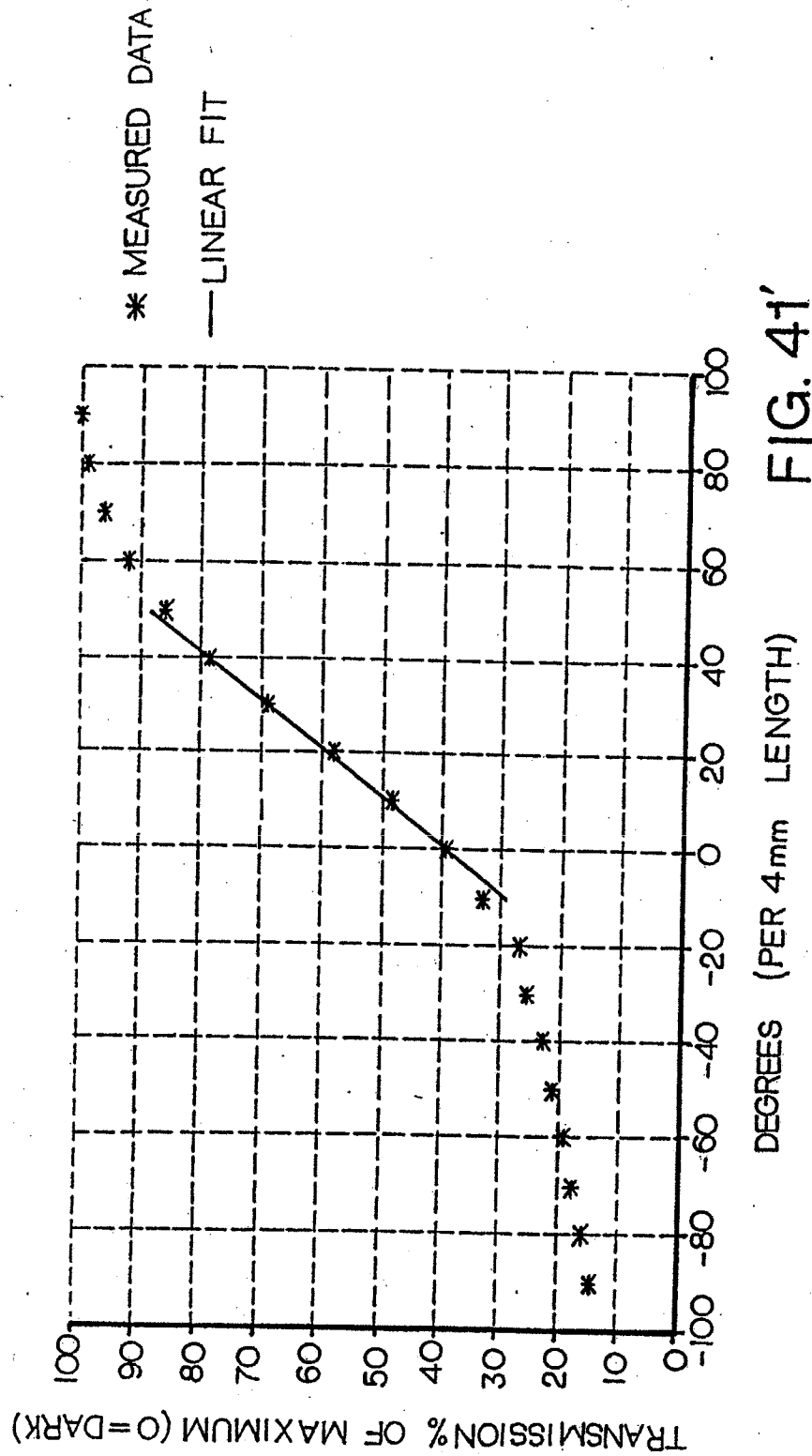
FIG. 41'

PHI 301694

A. CLASSIFICATION OF SUBJECT MATTER
IPC 5 . G01B11/18   G01D5/26

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 5   G01B   G01D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO,A,86 03832 (BELLHOUSE MEDICAL PRODUCTS LIMITED) 3 July 1986	1,5-7,9, 10,25
Y	see the whole document	17,18
A		23

Y	US,A,4 880 971 (DANISCH) 14 November 1989 cited in the application see column 3, line 37 - line 54; figures 4,5	17,18

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
18 August 1994	1 2. 09. 94

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Batteson, A

Form PCT/ISA/210 (second sheet) (July 1992)

4

PHI 301695

INTERNATIONAL SEARCH REPORT

.formation on patent family members

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO-A-8603832	03-07-86	EP-A- 0205531	30-12-86
US-A-4880971	14-11-89	NONE	

PHI 301696